AN EVALUATION OF THE U. S. NAVY STRATOSPHERIC EXTRAPOLATION EQUATIONS AND AN INTERCOMPARISON OF SEVERAL METHODS OF 100, 50 and 30-mb ANALYSES

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ABSTRACT

In 1960 the United States Navy Weather Research Facility, Norfolk, Virginia, (NWRF) derived a set of linear regression equations having as their purpose to extrapolate vertically height and temperature data up to the 100-,50-, and 30-mb levels. The equations are statistically evaluated, particularly for the latitude band 30-40 degrees, with a view toward improving their usage in objective analysis by the United States Navy Fleet Numerical Weather Facility, Monterey, California (FNWF). It is found that the equations' usefulness depends on the "normality" of the synoptic situation, but in general the subject re-evaluation agrees well with tests conducted by NWRF for previous years. An intercomparison of stratospheric analyses at 100-, 50-, and 30-mb, as produced by the Institute of Meteorology and Geophysics of Berlin, Germany, the United States Weather Bureau, the Third Weather Wing of the United States Air Force, and FNWF indicates the necessity of actual stratospheric data (not just regression equations) for analysis at polar latitudes. Several schemes for objective stratospheric analysis, involving minimal use of data, are suggested by the authors.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

TABLE OF SYMBOLS AND ABBREVIATIONS

011	=	Wheelus Air Force Base, Libya
122	=	Osan, Korea
274	=	Tuscon, Arizona
304	=	Cape Hatteras, North Carolina
327	=	Nashville, Tennessee
888	=	Ocean Station 'E'
999	=	Ocean Station 'V'
r	=	correlation coefficient
C	=	climatology
P	=	persistence
L	=	results obtained utilizing U.S. Navy Fleet Weather Research Facility linear regression equations
X	=	results obtained utilizing equation: $\frac{P}{2} + \frac{C}{2}$
USNAVPGSCOL	=	U. S. Naval Postgraduate School, Monterey, California
NWRF	=	U. S. Navy Fleet Weather Research Facility, Norfolk, Virginia
FNWF	=	U. S. Navy Fleet Numerical Weather Facility, Monterey, California
USAF	=	U. S. Air Force Third Weather Wing, Offutt Air Force Base, Omaha, Nebraska
USWB	=	Stratospheric Analysis Laboratory, U. S. Weather Bureau, Washington, D. C.
IMGB	=	Institute of Meteorology and Geophysics, Berlin, Federal Republic of Germany

1. Introduction

Accurate analyses of height and temperature at stratospheric levels are made difficult by the deficiencies of radiosonde data and the scarcity of data-reporting points. In the following paper, the authors present (i) an analysis of linear regression equations used to substitute for the lack of reliable data and, (ii) a comparison of the products of several meteorological groups producing analyses at 100-, 50-, and 30-mbs.

In 1960, Lea reported on a set of regression equations [1] which resulted from evaluating two years of International Geophysical Year data (July 1957 - June 1959) at NWRF. These equations, now widely accepted and used in operational analyses, are utilized to extrapolate 200-mb data to 100, 50, and 30 mbs. For instance, FNWF employs the equations for their 100-, 50-, and 30-mb analyses without the addition of actual data, while the USAF and USWB use the equations along with actual (corrected) data for their analyses.

A 1964 United States Naval Postgraduate School Bachelor's thesis investigation by Cave and Ritchie [2] compared the FNWF analyses with hand-analyzed charts produced by the IMGB. Their results cast some doubt on the exactness of the equations and the validity of the analysis technique employed by FNWF. After discussions with Dr. Robert Stinson, NWRF, Dr. Sidney Teweles, Stratospheric Analysis Laboratory, USWB, and Capt. Paul Wolff, FNWF, it was decided to embark on a research project to attempt to answer the following questions:

a. How well do extrapolations, using NWRF's equations, verify?

b. Can the equations be restratified by meteorological parameters, or in some other manner, to improve their performance?

c. How do current stratospheric analyses, analyzed daily by several agencies, compare?

A final aspect of the investigation is an attempt to determine if the present FNWF stratospheric analysis scheme is optimum in view of (a), (b), and (c) above.

2. Data

Data were obtained [3] for one year, March 1963 to February 1964, for the seven stations listed in the symbols table, page viii. All the stations are within the latitude band, 30N - 40N, and all were among the stations used by NWRF to calculate the regression equations.

Only the one latitude band was selected for intensive study because the research project was intended to be only a pilot study. FNWF and NWRF plan to extend the analysis if justified by the results. The particular band was selected because of the reported average accuracy of the equations there [1]. Also, the band intersects the middle of the United States where data are plentiful and includes an ocean station vessel in both the Atlantic and Pacific Oceans for which data were available.

All 00Z soundings for the selected stations which reached 30 mb were utilized. The data were classified by four parameters:

(P1) curvature of the contours at 200 mb,

(P2) tropopause above or below 200 mb,

(P3) cyclonic or anticyclonic side of the jet stream at the level of maximum winds, and

(P4) distance from the jet stream.

3. Evaluation of the Extrapolation Equations

The data were transferred to punch cards and an original Fortran 60 [4] program, for extrapolating the NWRF equations, was written for the Control Data Corporation 1604 computer at the USNAVPGSCOL. This program carries out the extrapolations, compares the results with the reported data, and prints out the individual errors, root-mean-square errors, mean errors, mean absolute errors, and their standard deviations. The program and data cards are on file with Professor Robert Renard, USNAVPGSCOL.

Results were initially checked by a desk calculator to insure the accuracy of the program. Also, for all large or abnormal errors, the data were rechecked to insure that they had been entered into the computer correctly. Results obtained from equations (3), (4), (7), and (8), Appendix 1, although computed, were not fully considered due to the fact that they are not utilized by FNWF, the USWB, or the USAF.

Originally, all the data were divided by months and extrapolations were made utilizing the aforementioned Fortran program. The results indicated that the equations work well. The root-mean-square errors were on the order of 25-30 m in height and 2-2.5C in temperature, with the small errors at the upper levels and for the shorter extrapolation intervals. These results are similar to NWRF's conclusions using independent data [1] and compare favorably with observational errors quoted in [5, 6]. However, it was noted that the errors varied markedly in magnitude, as denoted by large ranges and standard deviations. Some of these results are shown in Figs. 1 a-f. Also of note in these figures are the large errors in March, April, and December which will be referred to later.

In an attempt to find if the errors were systematic and related to the previously mentioned four meteorological parameters (p. 2), the data were further divided by each of the parameters and computer runs made. Comparison of the results for each parameter during each month were made by standard statistical methods [7], but nothing of significance was found. An example of the results may be seen in Tables 1-3.

At this point, it was decided that statistical significance in comparing the errors was not found because of a situation of the following type: a station normally in a cyclonic (anticyclonic) regime may have experienced large errors when anticyclonic (cyclonic) curvature occurred in the stratosphere above it; thus, significance of errors was concealed by grouping all stations together.

Therefore, the data were divided according to station number and the extrapolations once again performed. The results are shown in Figs. 2 a-f. One sidelight of note in these results is that the temperature errors of the stations in sunlight at 00Z all year long (999 and 122) were normally greater than the errors occurring at the stations in darkness (888 and 011).

This time, upon separating the data by the meteorological parameters mentioned on p. 2, the comparison of errors did show significance. The results for parameters P1 and P3 are shown in Tables 4-9. Differences in the parameter (as cyclonic vs. anticyclonic curvature for P1) at individual stations showed errors which were significantly different 13 times. Twelve of these occurrences indicated the equations performed better when the parameter which "normally" occurred over the station was in evidence. The other two parameters (P2 and P3) showed similar

results (not included here), but did not show significance due to the extremely few cases of the tropopause appearing below 200 mb and the high frequency of radiosondes not reaching 30 mb when the jet stream is very close to the station.

From the above, it may be assumed that the equations are based on short-period climatology. A careful study of monthly climatological charts for the period of NWRF's data [8] and the period of the authors' data [9] showed the largest differences between these charts to be located where the largest errors occurred in the computer runs discussed in the previous paragraph. Especially different were the months of March, April, and December, as mentioned on p. 3.

Therefore, it is felt that it would be possible to improve the equations by restratifying them using climatologically similar areas, particularly by the 200-mb curvature, in addition to latitude and to use seasons as well as months. Teweles has made a start in this direction with his new set of 30-mb to 10-mb extrapolation equations.[1] NWRF, in an attempt to improve its own equations, used longitude as a third stratifying parameter, with some small improvement in results.[1].

However, it was also recognized that the work and time involved in this sort of stratification would be excessive and the return for the effort may be small. Therefore, an attempt to improve the results of the equations by a statistical vice meteorological method was instituted.

The approach taken was similar to that described by Lavoie and Wiederanders [10] in which climatology and persistence are combined in

[1]Teweles, S., Memorandum to FNWF of 24 December 1964

a proportion depending on the correlation coefficient for persistence of the variable to be forecast. Four time spans, for which a continuous and long period of data was available, were found. Two of these spans occurred at Osan and one each at Nashville and Tucson. Extrapolations for these times were made utilizing NWRF's equations as climatology and assuming the correlation coefficient for persistence to be 0.5. Additional extrapolations for the same times were also made using pure persistence and using the equations in their unmodified form. Some of the results of these extrapolations are shown in Figs. 3 a-c, 4 a-c, and 5 a-b.

It will be noted in Figs. 5 a-b that NWRF's equations work better than the combination method for height extrapolation, but that the reverse is true for temperature extrapolations. This is to be expected because the correlation coefficients of NWRF's equations are much greater for height than for temperature. Also 24-hr persistence should be more accurate for temperature than for height due to the elimination of the diurnal effect. The great amount of large temperature errors in NWRF's equations at 30 mb are attributable to one station (Nashville) in December where it was much warmer than normal. At this station there were errors exceeding 3.4C for 11 consecutive days. Using the combination of climatology and persistence effectively eliminated this large amount of error without introducing much of an error elsewhere. Herein lies a suggestion for further research. A more accurate value for the persistence correlation coefficient than the assumed value of 0.5 would, perhaps, significantly improve the extrapolations.

In this same vein, Professor Robert Renard, USNAVPGSCOL, has

suggested another possible way to overcome the fact that the equations are apparently climatologically unstable. He suggested leaving the equations stratified as they are, but computing the regression coefficients on a continuing basis, such as always using the last 30 days or so of data for the computations. Although it is felt that this method has merit, no work was done on it due to the lack of time.

4. Intercomparison of Stratospheric Analyses

There are currently at least four organizations (USWB, USAF, IMGB, FNWF) producing stratospheric analyses on a daily basis. The authors compared these four products, all of which are produced by dissimilar methods, but three of which are produced using NWRF's equations in some manner.

The USWB utilizes a very precise and elaborate system as described by Finger and Woolf [11]. Their system uses checked and corrected data from three time periods, map time and 12 hours before and after map time. With these corrected data as input and a combination of NWRF's equations and persistence as a first-guess field, they objectively analyze the 100-, 50-, and 30-mb height and temperature fields.

USAF uses a system very similar to that of the USWB.[1] The primary difference between the two methods appears to be the system for reaching 100 mb. The USAF simply uses six-hr persistence as the first-guess field when analyzing at this level. When analyzing at 50 and 30 mb, they use the same method as the USWB.

[1]Information received partly by telephone conversation with members of the United States Air Force Third Weather Wing.

The IMGB charts at stratospheric levels are produced, apparently, by means of a hand analysis with emphasis on continuity and persistence.

FNWF arrives at their analyses by use of the extrapolation equations, starting from their 200-mb chart data and simply extrapolating to the 100-, 50-, and 30-mb levels with no addition of reported data. In this comparison, the major emphasis has been placed on trying to determine if FNWF's method yields satisfactory results.

For the purpose of this phase of the investigation a six-day period, 10-15 January, 1965, was selected. These recent dates were selected in order to be able to use 200-mb products from FNWF which were based on their newest model. Finger and Woolf [11] described this period as one of large-scale circulation changes which were being accompanied by moderate stratospheric warming.

Between the USAF and USWB charts there was little difference. This is, of course, quite understandable due to the similarity of the methods by which the analyses are produced. The charts produced by the USWB and IMGB are not directly comparable because they are analyzed at different times. The IMGB produces a 00Z chart while the USWB produces a 12Z chart. However, both of these can be compared to FNWF which produces both a 00Z and a 12Z analysis. These comparisons are the subject matter of this section. Of the six days which were studied, one day, 12 January, will be fully discussed. This day is representative of the entire period. Data and analyses for the other days are on file with Professor Robert Renard, USNAVPGSCOL.

It will be noted that the height-difference patterns drawn and utilized in the comparison section have different base heights. This is

caused by the fact that the original analyses produced by the several organizations were drawn with different intervals and, in the case of the IMGB product, different base heights. Rather than to attempt visually to interpolate between the contours, base heights similar to those used by FNWF were selected for the difference patterns, thus causing the IMGB difference patterns to appear inconsistent. In every case the interval used at 100 and 50 mb is 240m and that at 30 mb is 480 m. All temperature difference patterns are at 5C intervals. No temperature data were available on the IMGB 50- and 30-mb analyses.

FNWF vs. IMGB 0000Z 100 mb Figs. 6,7,8

At 100 mb, both charts exhibit a five-wave situation with a bipolar cyclonic vortex. The troughs are (1) over the Bering Sea, (2) over central Canada and the western United States, (3) over the British Isles extending to the Iberian Peninsula, (4) over Eastern Europe extending to the Black Sea, and (5) over Central Asia. Trough (1) is similarly placed on both charts but with FNWF indicating lower heights. Trough (2) is placed very similarly on each chart with both analyses indicating the same heights. Troughs (3), (4), and (5) are also placed in approximately the same positions. From an overall viewpoint the patterns are exceedingly similar with the main differences coming from the large number of small perturbations present in the FNWF analysis. The difference pattern, Fig. 8, indicates some small random differences mostly associated with trough (1). The maximum difference is about equal to 380 m and occurs over the Northern Pacific Ocean.

FNWF vs. USWB 1200Z 100 mb Figs. 9,10,11,12

The 12Z pattern again exhibits the same five troughs that were obvious in the 00Z pattern. Trough (1) is located similarly and has about the same heights with the FNWF pattern showing much more detail in the curvature. The FNWF chart has a closed -50C isotherm in this trough while the USWB has a -42C center. Trough (2) is more pronounced on the USWB chart; both the heights and temperature in this area are quite comparable. Trough (3) is now located between Greenland and the British Isles on the USWB chart. The temperatures indicated in this trough are somewhat colder according to the USWB analysis. Trough (4) is again located in approximately the same place as before, with comparable temperatures and heights. Trough (5) is also basically situated in the same place but the FNWF chart indicates several short-wave perturbations in the area. Again, as with the 00Z chart comparison, there are no areas yielding large differences. In the height difference pattern, Fig. 11, there are several scattered areas of about 240 m difference. The temperature difference pattern has a closed -15C difference over eastern Siberia.

FNWF vs. IMGB 0000Z 50 mb Figs. 13,14,15

The circumpolar vortex now has a single center. The trough which was over the Bering Sea at 100 mb is in almost the same position at 50 mb on the FNWF analysis. Such a trough is not evident on the IMGB chart; instead the isohypses indicate zero or anticyclonic curvature. Geostrophic winds computed in this area at position 35N 145E are 40 kt from 270° on the FNWF chart and calm on the IMGB chart. The trough

which was over the western United States at 100 mb on both charts is still in the same position at 50 mb. The trough extending over the Black Sea appears to be similar on both analyses; however, FNWF has small perturbations in the trough in the vicinity of 65N causing a difference of greater than 280 m in this area. However, the main difference area is over the Northern Pacific and Kamchatka Peninsula where the difference approaches 800 m which constitutes 47 percent of the hemispheric height range at this level on this date.

FNWF vs. USWB 1200Z 50 mb Figs. 16,17,18,19

The FNWF chart now shows a ridge over the eastern portion of the Bering Sea while the western part and the Kamchatka Peninsula are dominated by a trough. The USWB analysis shows almost straight contours with a very weak trough extending into the Pacific. The heights on the FNWF analysis are considerably lower than that of USWB, one reason being the position of the polar low. The low is almost over the pole on the FNWF product but is centered over Northern Greenland and the Labrador Sea on the USWB version. This difference in position along with similar gradients causes the charts to have vastly dissimilar heights over Asia. The central Asian area is also much colder on the FNWF analysis. On the European side the two patterns have a radically different appearance, both in height and temperature, but do not have large differences in either. However, winds computed from these contours vary greatly in direction: at position 50N 10E the USWB has winds of 32 kt from 270° while at the same position FNWF has winds of 32 kt from 185°. The FNWF pattern, as on all the other charts so far discussed, has

many small perturbations which do not show up on the other analyses. At 100 mb the differences were small and scattered, but at this level the differences are becoming large, reaching a value of 520 m over Siberia. This represents 32 percent of the hemispheric height difference. The temperature pattern shows a small closed -30 C isotherm over Siberia.

FNWF vs. IMGB 0000Z 30 mb Figs. 20,21,22

The area of prime interest on this chart is once again over the Bering Sea and eastern Russia. FNWF continues to analyze a trough extending over the Kamchatka Peninsula with a low-pressure area almost surrounding a sharp ridge over the eastern Bering Sea. The IMGB product indicates a closed high centered over the Bering Sea with no indication of a trough over Kamchatka. These differences lead to a maximum difference of 1460 m in the pattern in this area. In addition, FNWF indicates stronger gradient south of the tip of Greenland causing the FNWF pattern to show somewhat higher heights in this area as is shown on the difference pattern. Again, at this level, an excessive number of small perturbations are apparent on the FNWF analysis. These large differences lead to radically different computed geostrophic winds as indicated in Table 10.

FNWF vs. USWB 1200Z 30 mb Figs. 23,24,25,26

As with the IMGB comparison at this level the primary area of interest is over eastern Russia. FNWF places a trough over the Kamchatka Peninsula extending into the Northern Pacific. In this area, the temperature patterns indicate a difference of over 30C. On the European

side of the pole FNWF's pattern again becomes erratic in both height and temperature with sharp changes of curvature which are not shown on the USWB version. The difference charts in this area show large areas of differences up to 650 m and in excess of 15 C, with FNWF indicating the higher heights and temperatures. The maximum height difference, which is found over Siberia in the same position as the maximum temperature difference, reaches a value equal to 52 percent of the total hemispheric height difference. Geostrophic wind differences are illustrated in Table 10.

5. Summary of Comparisons

It should be noted that the value of the differences indicated in the difference patterns increases with increasing height. With both the IMGB and the USWB comparisons the differences appear to be randomly scattered at 100 mb but acquire more consistency of position with an increase of height. Both sets of 50- and 30-mb comparisons show differences of approximately the same magnitude and in the same positions. The range of differences varies from 240 m on the 12Z 100-mb comparison to 1460 m on the 00Z 30-mb comparison. The consistency of the 00Z and 12Z comparisons at the same heights and the similarity of the USAF analysis to that of USWB indicates that FNWF's method of using the equations only with no additional data <u>is not satisfactory, at least during the period tested</u>. It is also of note that Figs. 27-32 indicate that there is more consistency between the IMGB 00Z and the USWB 12Z charts than there is between the FNWF 00Z and 12Z charts.

FNWF analyzed a trough at 100, 50, and 30 mb over the Bering Sea.

However, both the IMGB and USWB, which utilize actual data, analyze a trough at 100 mb which becomes an anticyclonic region by 30 mb. A contributing factor to this is the moderate stratospheric warming taking place in this area which is apparently not properly handled by the extrapolation equations. When the temperature patterns of the various analyses which utilize actual data were compared to climatic charts of the upper atmosphere for the period from which the equations were derived [8], it was noted that the climatological temperatures were considerably colder than those of the current analyses in the areas of large negative height and temperature differences and moderately warmer in the areas of positive differences.

6. Conclusions and Recommendations

In considering the conclusions, the reader is again reminded that the project was intended to be a pilot study in order to guide FNWF and NWRF to further work on this problem if it was felt to be necessary.

First, the equations did work well in the areas where the synoptic situation during the test period was similar to that which occurred when the equations were derived by NWRF. The test charts and extrapolations done with the computer both indicated this fact. However, "non-climatological" situations produced unexpectedly high errors. These were found for the most part in March, April, and December by the computer program and over Siberia and the Kamchatka Peninsula by the chart comparisons.

Results agreeing with the conclusions mentioned above were obtained when a spot check of other latitude bands was made using the computer. Similar results were also arrived at when comparison of charts during

February and May 1965 was accomplished. Therefore, the equations are assumed to be climatologically unstable and satisfactory results cannot be obtained on a continuing basis without the addition of current data. However, the aim of the suggested changes which follow, is to alter the equations as little as possible and still correct the deficiencies noted above.

The first suggestion has to do with restratification of the equations by meteorological parameters. The authors feel that this could be accomplished using season and climatologically similar areas based on parameters P1 or P3. However, although this would improve the results of the equations, it would involve considerable work and would not cure the equations of their basic fault - their inability to respond to present upper-air conditions. Also this would result in changing the equations greatly from their present simple form.

Therefore, it is felt that the method of using the equations as climatology and modifying them by persistence would be an easier and more effective remedy. With a better correlation coefficient computed for 24-hr height and temperature persistence, the results of this method would be even better than those obtained by the authors. This system would enable the equations to respond to the present meteorological situation in the stratosphere, which they cannot do at the present time. It is realized that FNWF has reasons for not desiring to process stratospheric data. However, because the data would be used as persistence, there would be no hurry in processing it nor would its exact value be of so great an import as it would be in the case of present data to be analyzed.

Several other approaches were tested to find an acceptable method of analysis which would not necessitate FNWF processing data, but would still alter the results of FNWF's analysis to fit the current stratospheric regime. One such approach considered using 24-hr old analyses, as analyzed by the USWB, as the present chart. This method greatly reduced the differences in the areas of very large errors but introduced random errors elsewhere which are seemingly unpredictable in position and magnitude (Fig. 33).

Another approach[1] is to use the 24-hr old difference pattern between FNWF and USWB analyses. This difference pattern is added to the present FNWF analysis. The results of this method were, once again to drastically reduce the differences in areas where there had been large differences. Moreover, it did not introduce such large random differences in other areas and on a continuing basis should produce fewer differences due to the fact that the equations work better than persistance as has been shown (Fig. 5 a-b). This method should give acceptable results with no further research required other than some checking of the method itself, and also eliminates the need for FNWF to process current data. This method was checked by the authors for the test charts in January 1965 and further checked by random sampling of dates in February and May 1965. Fig. 34 is an example of results obtained in this manner.

Summing up, the authors feel that the equations work well except for

[1]Suggested in conversation with Mr. Leo Clarke, FNWF

times when the synoptic situation is not similar to that encountered in 1957-59. The only solution to this problem is the introduction of observations, in some form, the stratospheric constant-pressure analyses.

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TABLE 1

STRAIGHT FLOW

EQ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	25.0	30.0	40.6	22.9	20.7	28.3	26.0	22.5	24.1	25.5	26.4	29.9
2	1.9	2.0	3.0	1.7	1.6	1.8	2.0	1.9	2.1	2.0	1.8	2.2
5	26.0	21.0	26.3	14.8	24.4	23.2	20.2	18.9	24.1	19.9	24.0	32.0
6	1.8	1.6	2.2	1.8	2.0	1.3	1.4	1.3	1.9	1.8	1.8	2.5
9	22.0	14.9	17.5	16.6	18.3	17.5	14.1	11.7	13.7	15.2	14.7	29.9
10	2.3	1.8	2.5	1.9	2.1	1.4	1.4	1.1	1.4	1.6	1.1	4.0
#	66	72	83	54	77	53	59	69	61	64	87	91

Height errors in meters, temperature errors in ^{o}C

= number of cases

TABLE 2

ANTICYCLONIC CURVATURE

EQ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	26.4	29.6	28.6	37.5	21.5	26.5	24.3	25.1	25.0	23.9	18.6	28.4
2	1.9	1.6	2.4	1.9	1.6	2.3	2.3	2.1	2.1	2.0	1.6	1.7
5	21.8	18.0	27.4	26.4	23.8	22.0	25.0	19.1	23.1	24.0	26.5	26.7
6	1.6	1.7	1.9	1.7	2.2	1.5	1.4	1.3	2.0	1.7	1.7	2.2
9	17.5	15.1	18.7	20.5	13.9	13.7	13.3	14.1	13.7	13.3	12.8	18.3
10	1.9	1.8	2.5	2.2	1.9	1.2	1.7	1.5	1.4	1.3	1.6	2.4
#	18	22	40	50	38	49	82	63	52	54	44	35

TABLE 3

CYCLONIC CURVATURE

EQ	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	22.5	17.6	30.0	31.3	28.2	27.3	25.0	21.7	28.8	28.8	25.3	24.4
2	1.5	1.7	2.3	2.0	1.6	2.3	2.0	1.6	2.2	2.2	1.8	1.7
5	26.4	20.2	27.2	23.3	29.9	25.9	20.3	19.6	21.8	19.4	30.4	24.1
6	2.3	1.9	2.1	1.8	1.5	1.5	1.4	1.2	1.7	1.7	2.0	2.8
9	18.0	14.7	17.8	19.1	14.8	15.2	15.1	12.0	12.7	14.8	17.8	21.6
10	2.1	1.7	2.0	2.2	1.5	1.6	1.7	1.2	1.4	1.3	1.7	3.0
#	44	50	60	74	54	85	56	69	63	69	49	39

TABLE 4

STRAIGHT FLOW

EQ	274	888	999	304	011	122	327
1	23.5	29.8	25.1	27.1	27.4	27.8	29.2
2	2.2	1.8	2.2	1.9	2.0	2.0	2.1
5	21.6	20.4	20.6	21.9	26.6	23.3	25.7
6	1.5	1.5	2.2	1.8	2.1	1.9	1.7
9	20.5	14.8	15.7	19.3	14.0	19.9	17.8
10	2.5	1.9	1.8	2.2	1.6	2.1	1.9
#	96	93	85	119	114	176	114

TABLE 5

ANTICYCLONIC CURVATURE

EQ	274	888	999	304	011	122	327
1	19.6	30.6	24.5	26.3	27.5	30.8	24.8
2	1.9	1.9	2.4	2.2	1.9	1.8	2.0
5	27.2	20.1	26.9	22.8	22.9	26.2	21.0
6	1.7	1.5	1.9	1.7	1.8	1.8	1.5
9	16.4	12.5	13.7	16.5	15.1	18.8	16.2
10	2.1	1.5	1.9	1.8	1.7	2.1	1.6
#	88	92	84	50	80	44	77

TABLE 6

CYCLONIC CURVATURE

EQ	274	888	999	304	011	122	327
1	24.6	30.2	28.7	25.5	25.6	24.8	25.7
2	1.8	1.9	1.9	1.9	2.0	2.0	2.0
5	32.3	19.7	30.4	20.8	27.2	21.8	25.4
6	1.9	1.3	2.1	1.3	2.0	1.9	1.9
9	19.1	14.0	12.5	14.7	15.7	17.7	16.3
10	2.4	1.8	1.4	1.6	1.5	1.9	1.6
#	83	80	68	112	114	128	90

TABLE 7

JET STREAM OVER 300 MILES

EQ	274	888	999	304	011	122	327
1	21.1	30.1	25.5	25.9	26.8	27.4	24.3
2	2.2	1.8	2.2	2.1	1.9	1.9	2.0
5	25.2	18.7	28.1	22.1	25.0	21.5	23.4
6	1.7	1.5	1.9	1.5	2.0	1.7	1.6
9	18.3	13.4	13.7	15.1	15.5	17.2	15.6
10	2.3	1.6	1.7	1.6	1.5	1.9	1.6
#	141	201	170	106	227	222	101

TABLE 8

ANTICYCLONIC SIDE

EQ	274	888	999	304	011	122	327
1	23.6	30.9	26.3	27.1	27.8	26.9	26.4
2	1.6	2.2	2.0	1.9	2.0	2.1	2.0
5	28.7	23.7	34.7	21.7	25.5	25.2	26.3
6	1.6	1.4	2.6	1.6	1.9	1.9	1.7
9	16.3	14.3	14.1	18.8	13.4	22.3	17.7
10	1.9	2.0	1.7	2.0	1.7	2.4	1.5
#	54	47	45	115	48	64	104

TABLE 9

CYCLONIC SIDE

EQ	274	888	999	304	011	122	327
1	24.9	31.3	26.6	25.8	25.2	26.1	30.9
2	2.0	1.8	2.3	1.8	2.2	2.0	2.1
5	20.0	26.7	27.0	20.4	31.8	26.7	23.8
6	1.8	1.5	2.4	1.5	2.0	2.6	1.9
9	21.0	17.2	13.9	16.8	12.9	21.6	17.5
10	2.6	2.2	2.1	2.2	1.6	2.3	2.2
#	73	17	22	60	33	62	79

TABLE 10

Comparison of Geostrophic Winds at 30 mb

Position	FNWF	CURV	IMGB	CURV	Magnitude of Difference
51N/164E	265/72	cyc	095/17	acy	89
67N/139E	275/28	acy	235/39	0	25
68N/170W	255/68	cyc	280/44	0	33
48N/167W	calm	0	155/20	acy	20
64N/154W	250/84	acy	220/24	0	71

Position	FNWF	CURV	USWB	CURV	Magnitude of Difference
53N/160E	270/24	cyc	250/36	acy	16
52N/174E	180/40	acy	090/37	acy	54
61N/161W	285/72	cyc	310/24	acy	51
58N/110E	275/38	cyc	240/40	cyc	24
64N/147W	260/56	cyc	300/58	0	38

[illegible]

[illegible]

[illegible]		[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]
		[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
			[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]				[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]		[illegible]		[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

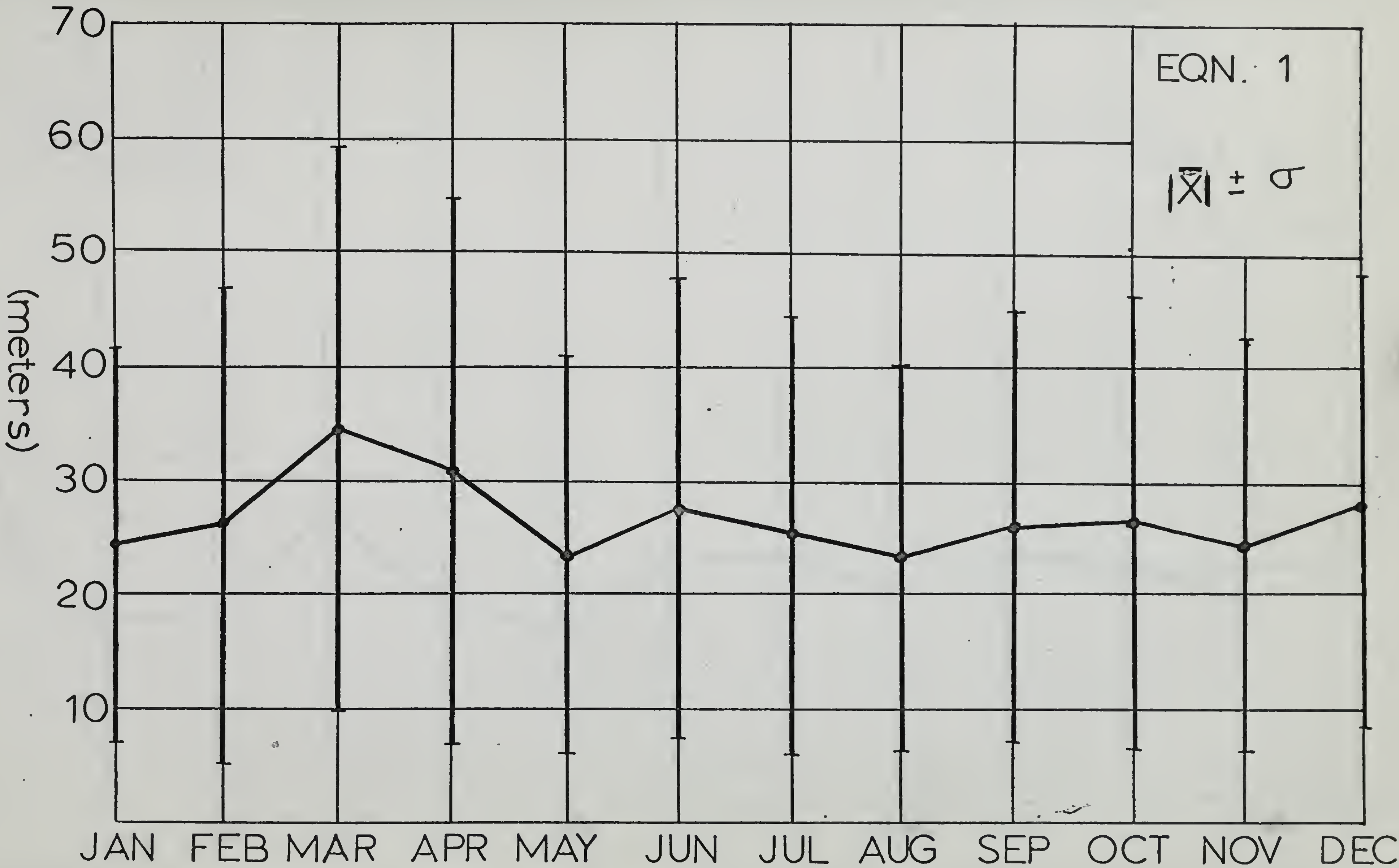

EQN. 1
$|\bar{X}| \pm \sigma$
70
60
50
40
30
20
10
(meters)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FIG. 1a

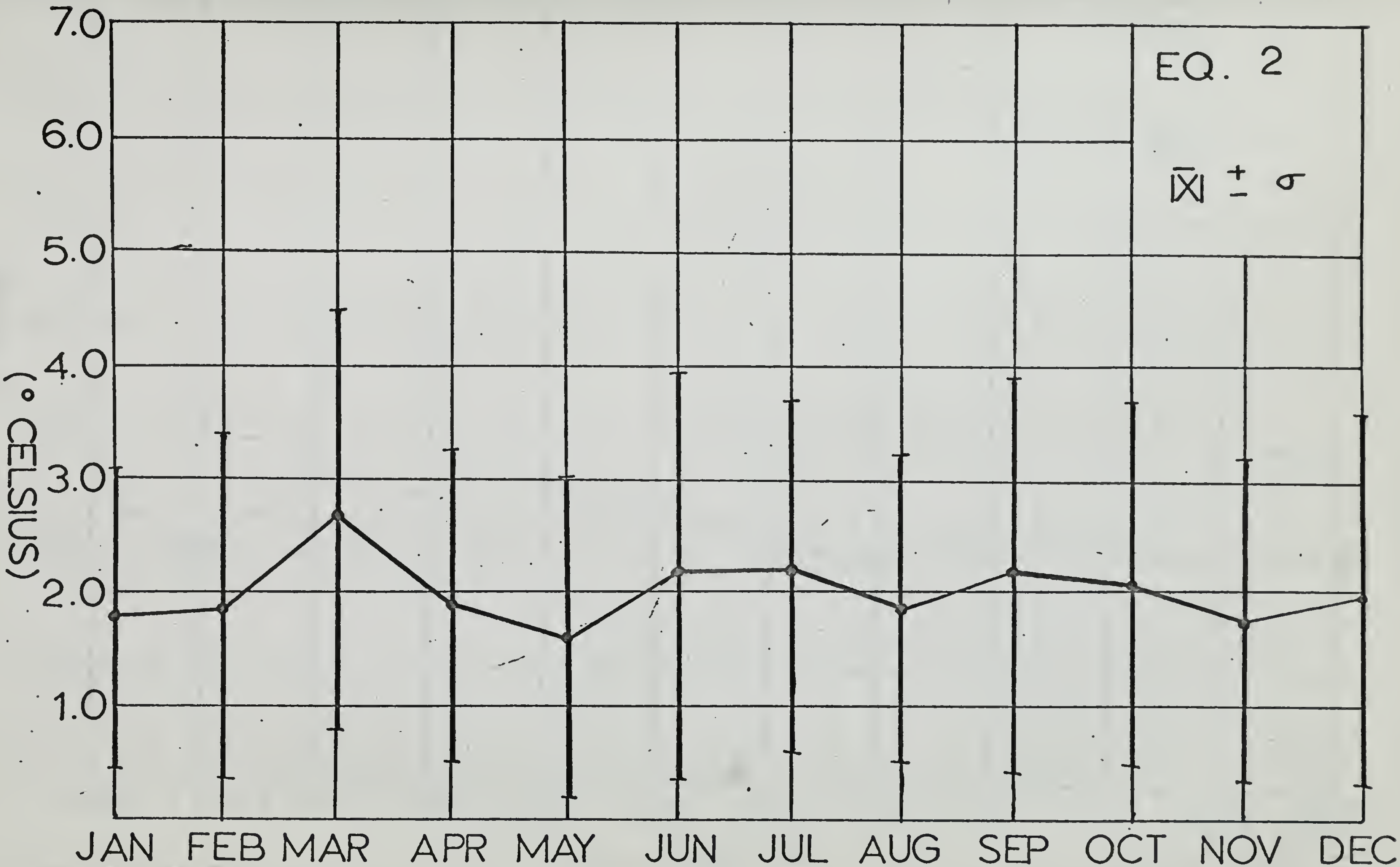
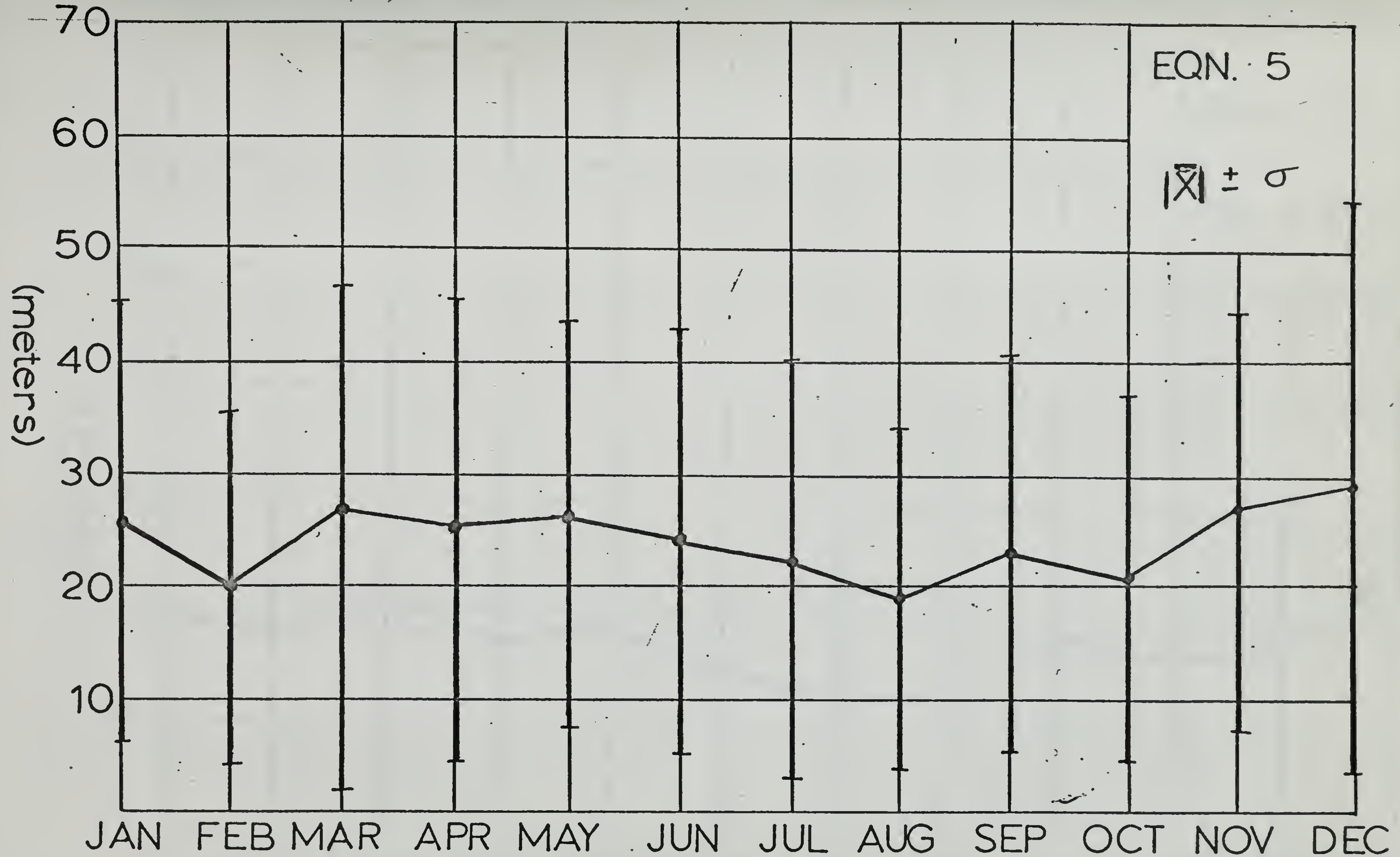

EQ. 2
$\bar{X} \pm \sigma$
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° CELSIUS)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FIG. 1b



EQN. 5
$|\bar{X}| \pm \sigma$
70
60
50
40
30
20
10
(meters)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

FIG. 1c

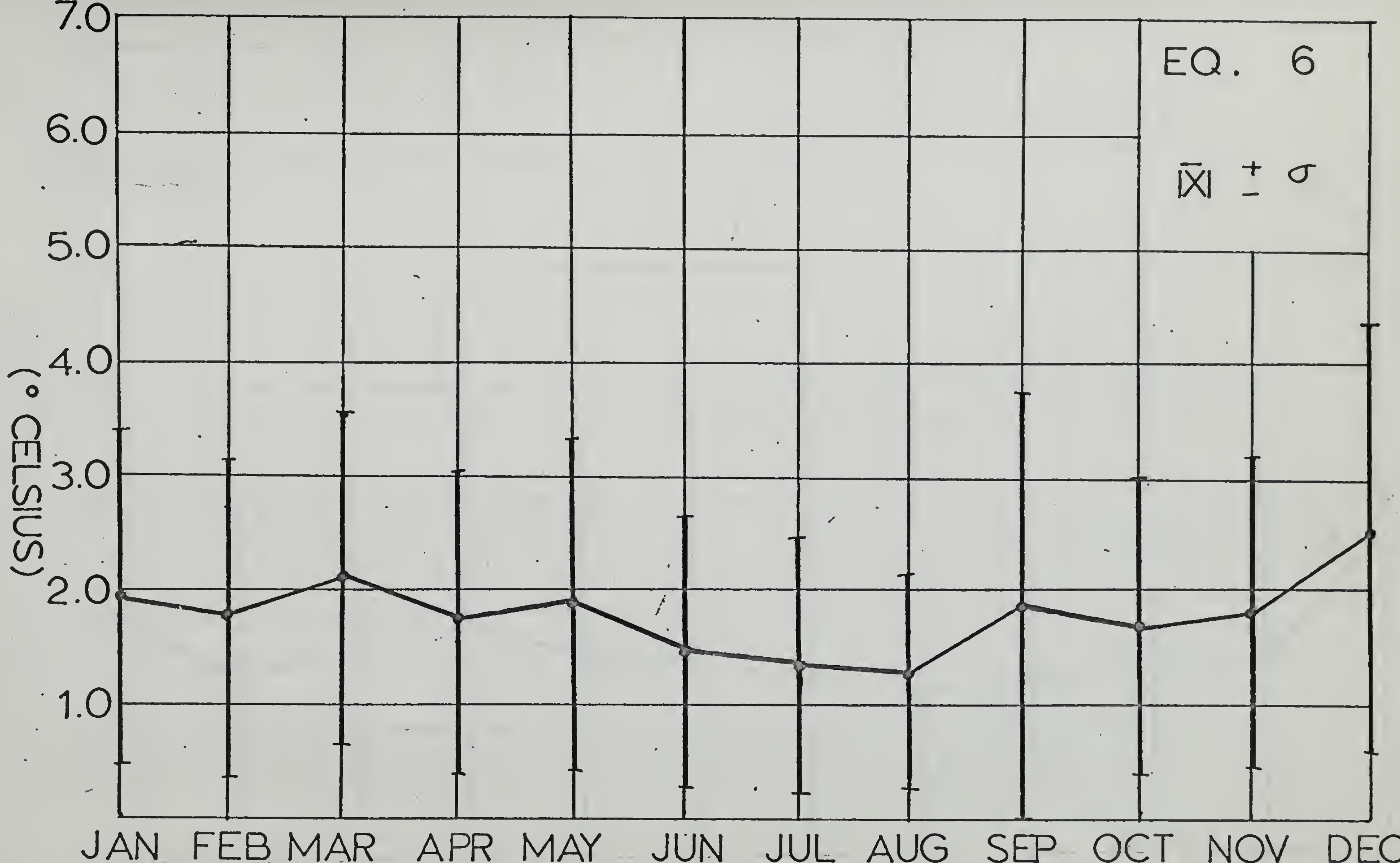

EQ. 6
|X̄| ± σ
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° CELSIUS)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FIG. 1d

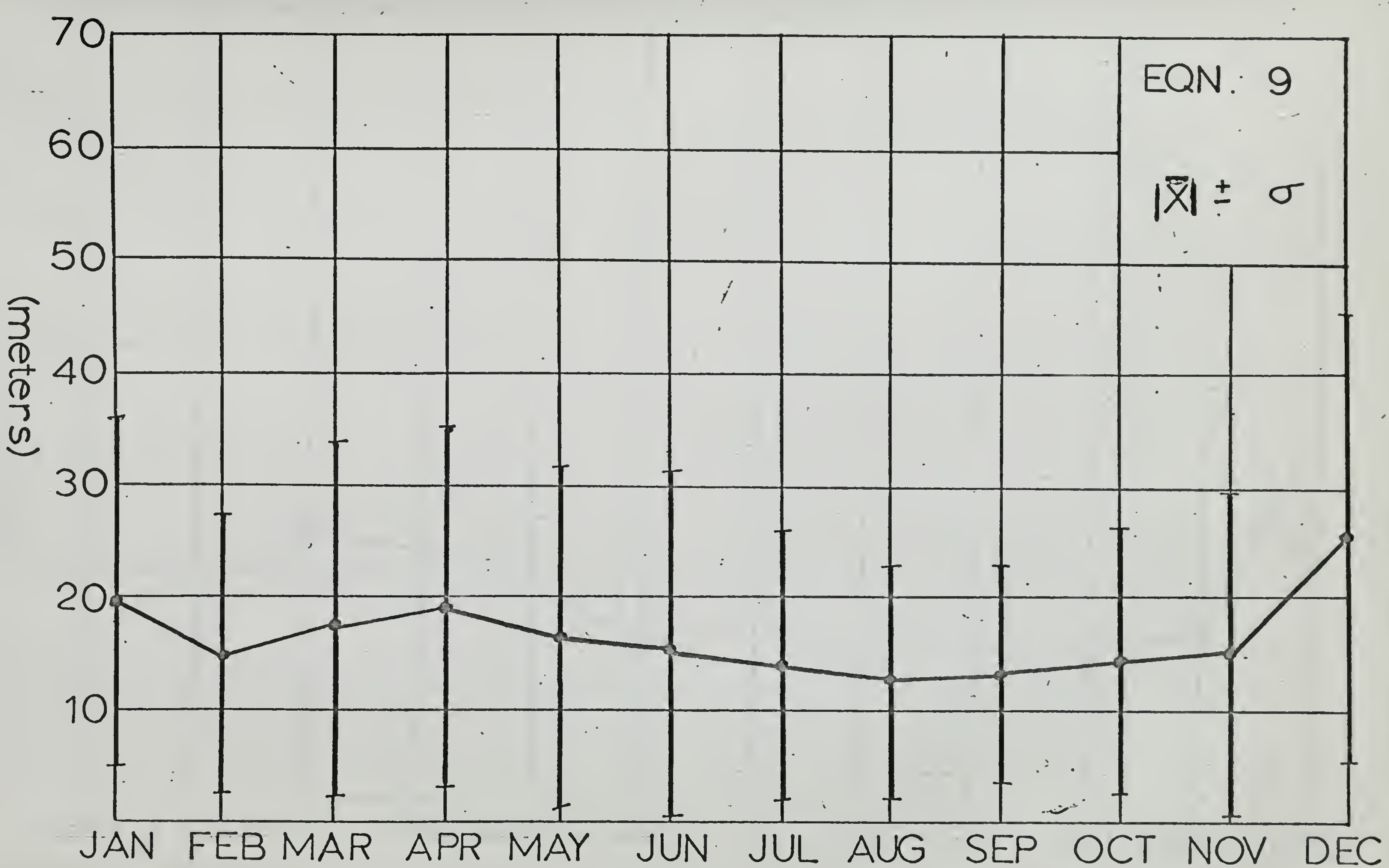

EQN. 9
$|\bar{X}| \pm \sigma$
70
60
50
40
30
20
10
(meters)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FIG. 1e

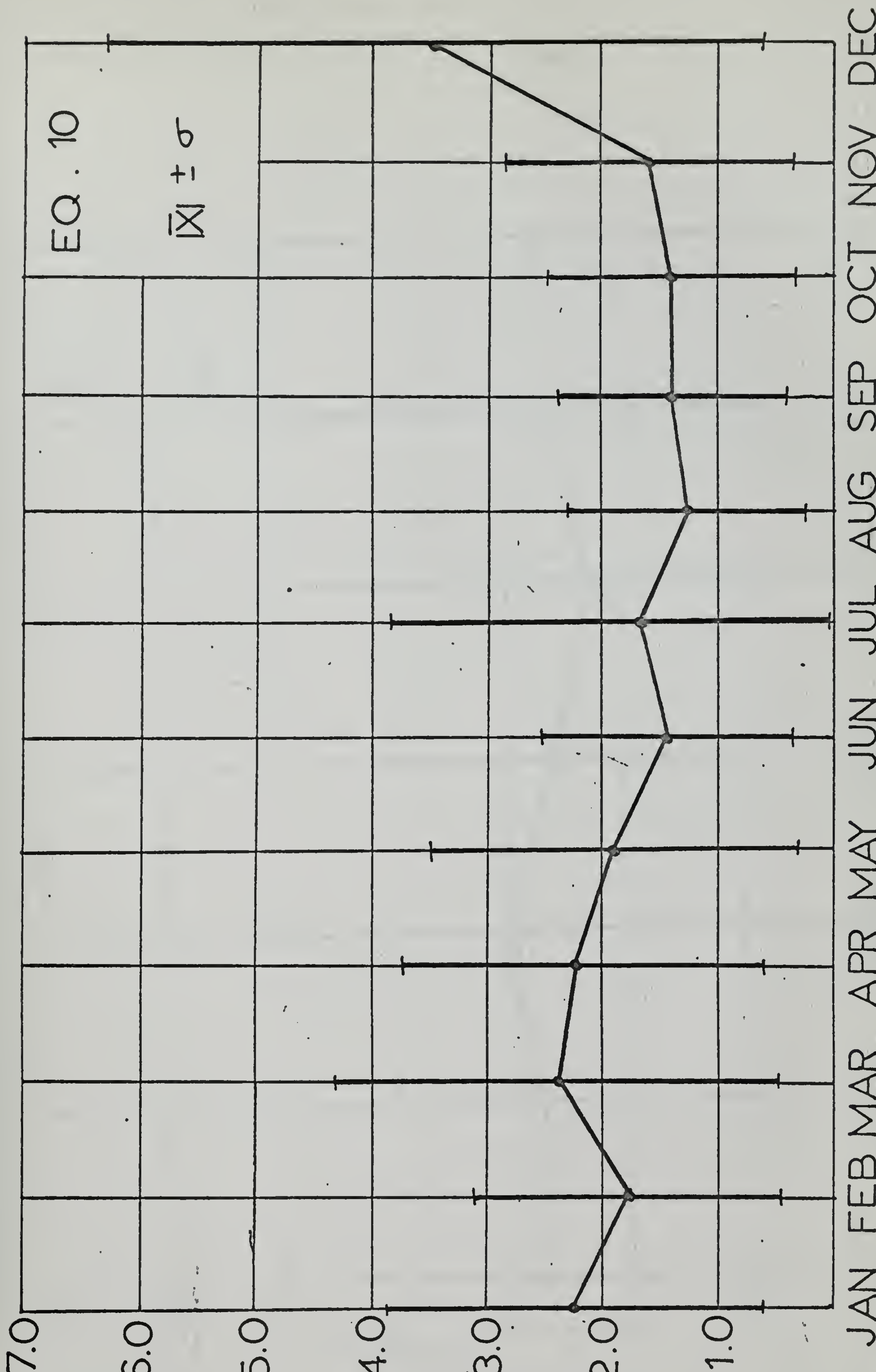
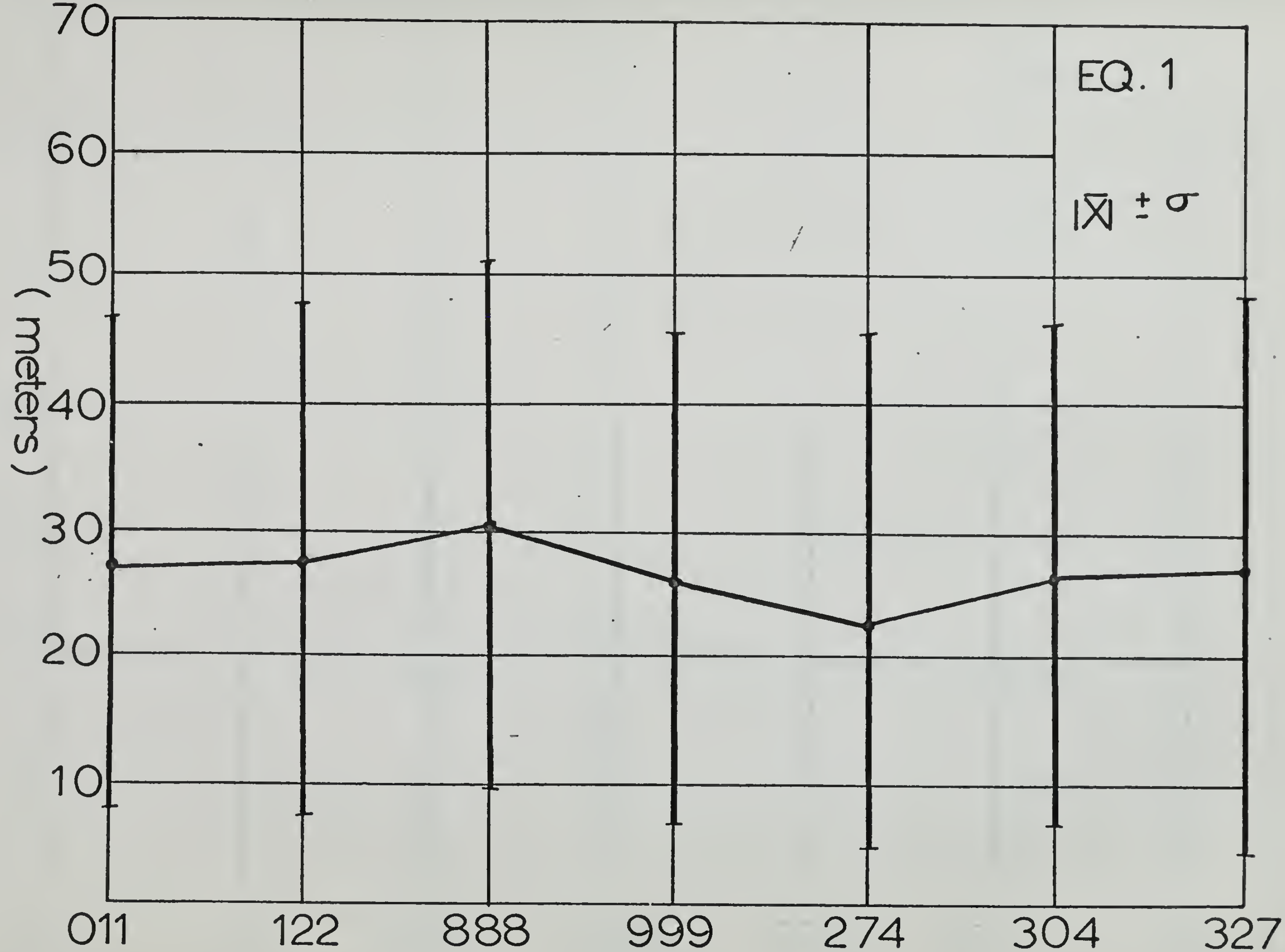

EQ. 10
$|\bar{X}| \pm \sigma$
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° CELSIUS)
JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

FIG. 1f



70
60
50
40
30
20
10
(meters)
EQ. 1
$|\bar{X}| \pm \sigma$
011
122
888
999
274
304
327

FIG. 2a

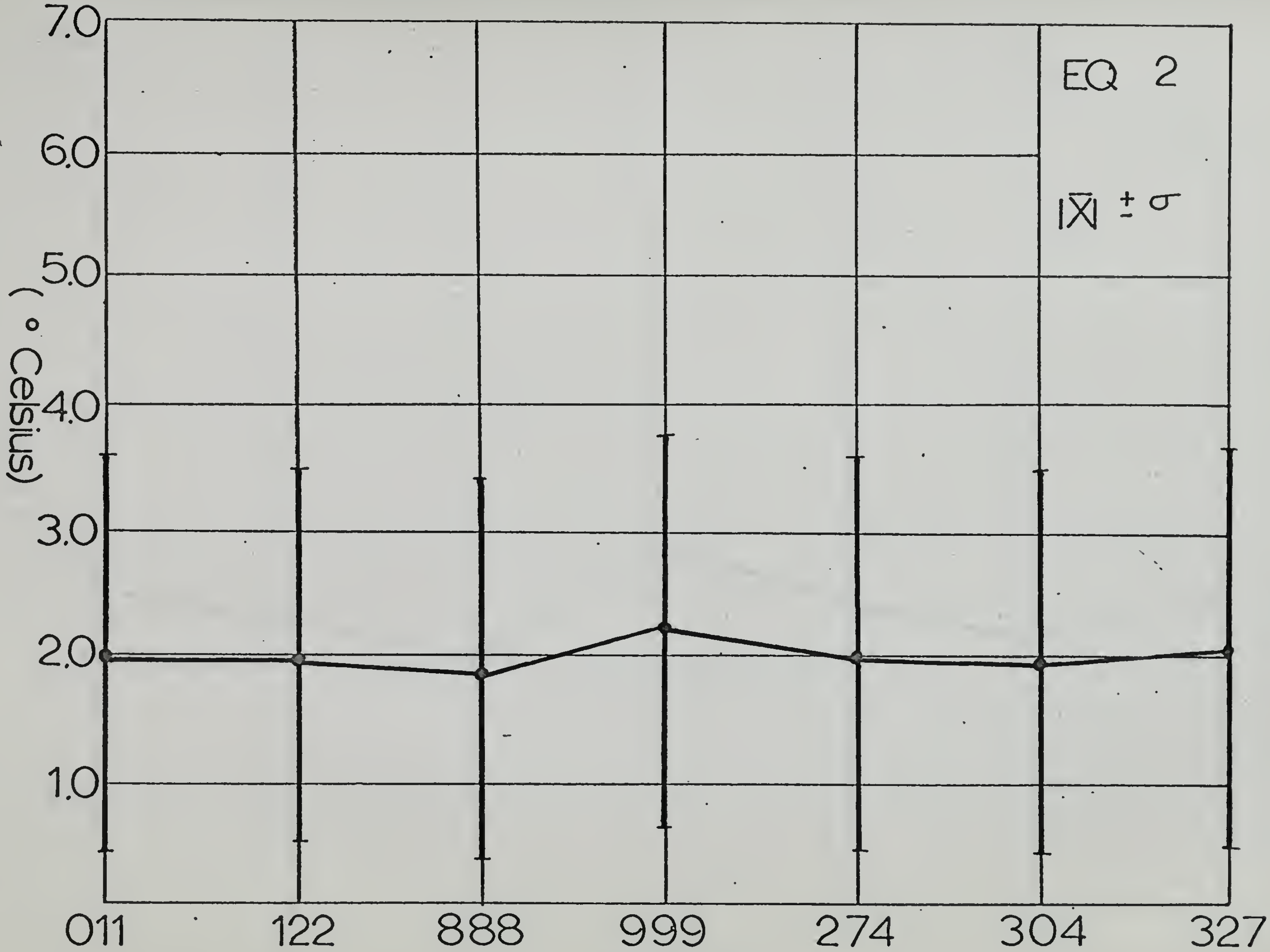


FIG. 2b

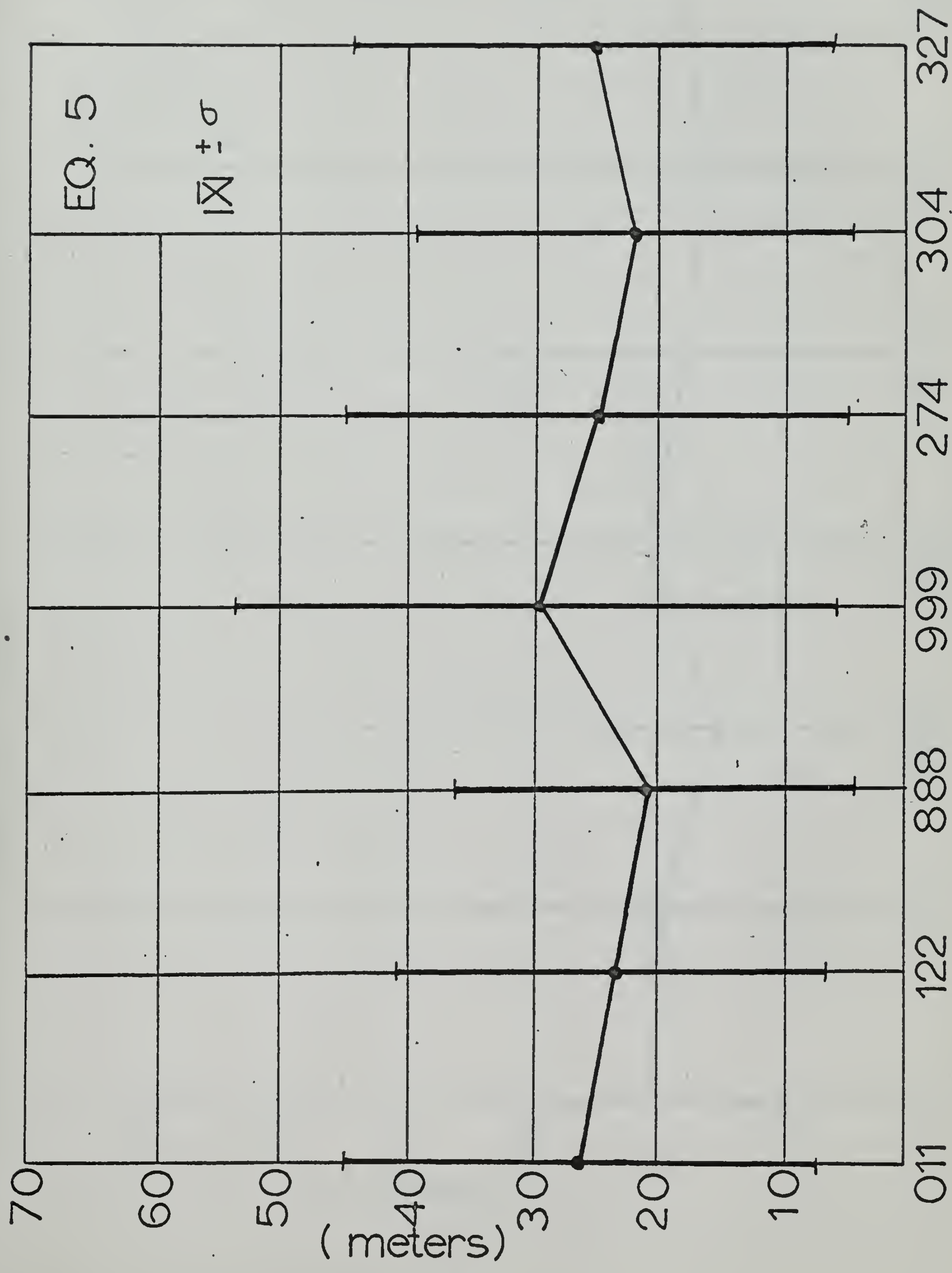

EQ. 5
$|\bar{X}| \pm \sigma$
70
60
50
40
30
20
10
(meters)
011
122
888
999
274
304
327

FIG. 2c

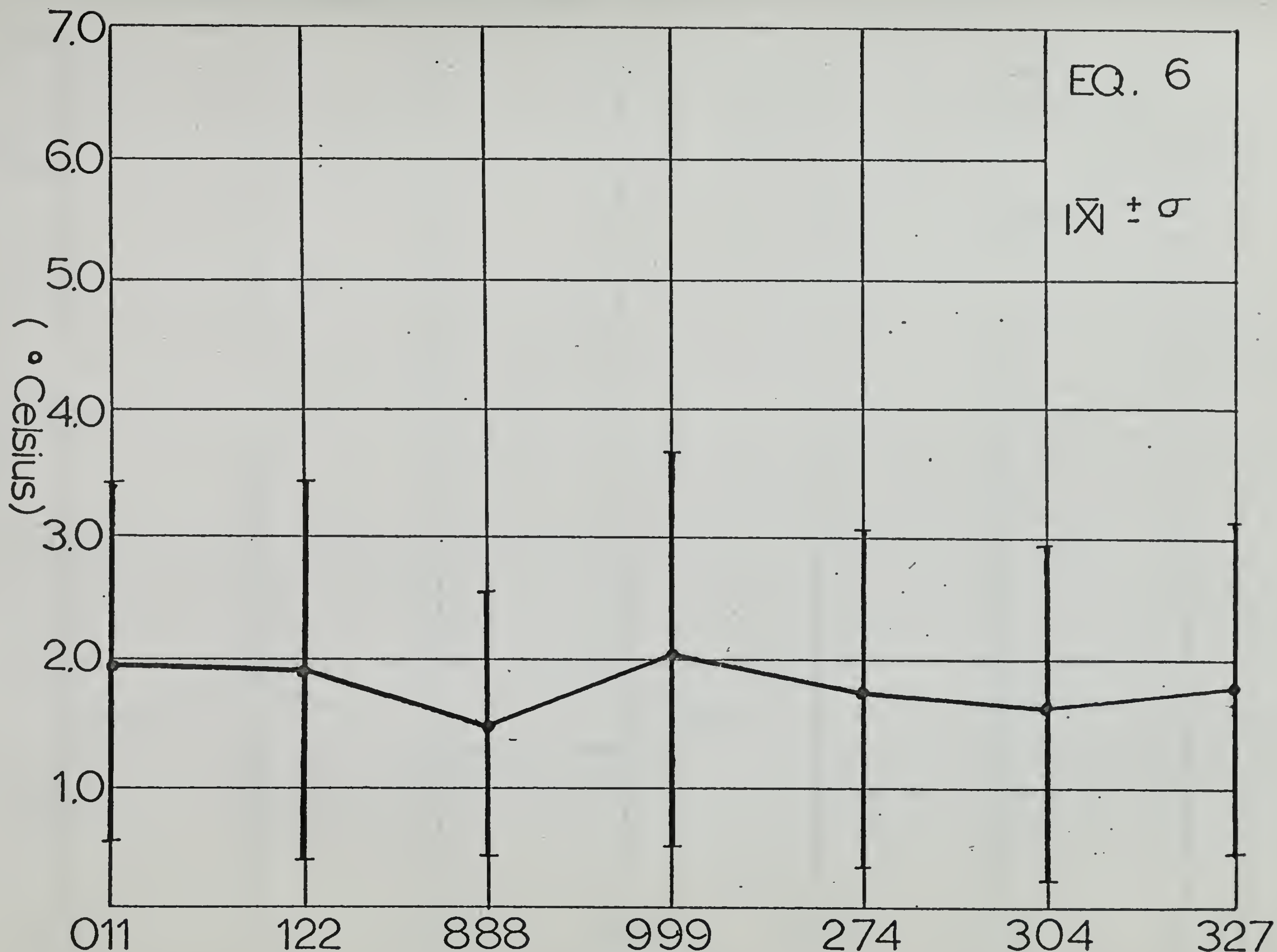

7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° Celsius)
011
122
888
999
274
304
327
EQ. 6
$|\bar{X}| \pm \sigma$

FIG. 2d

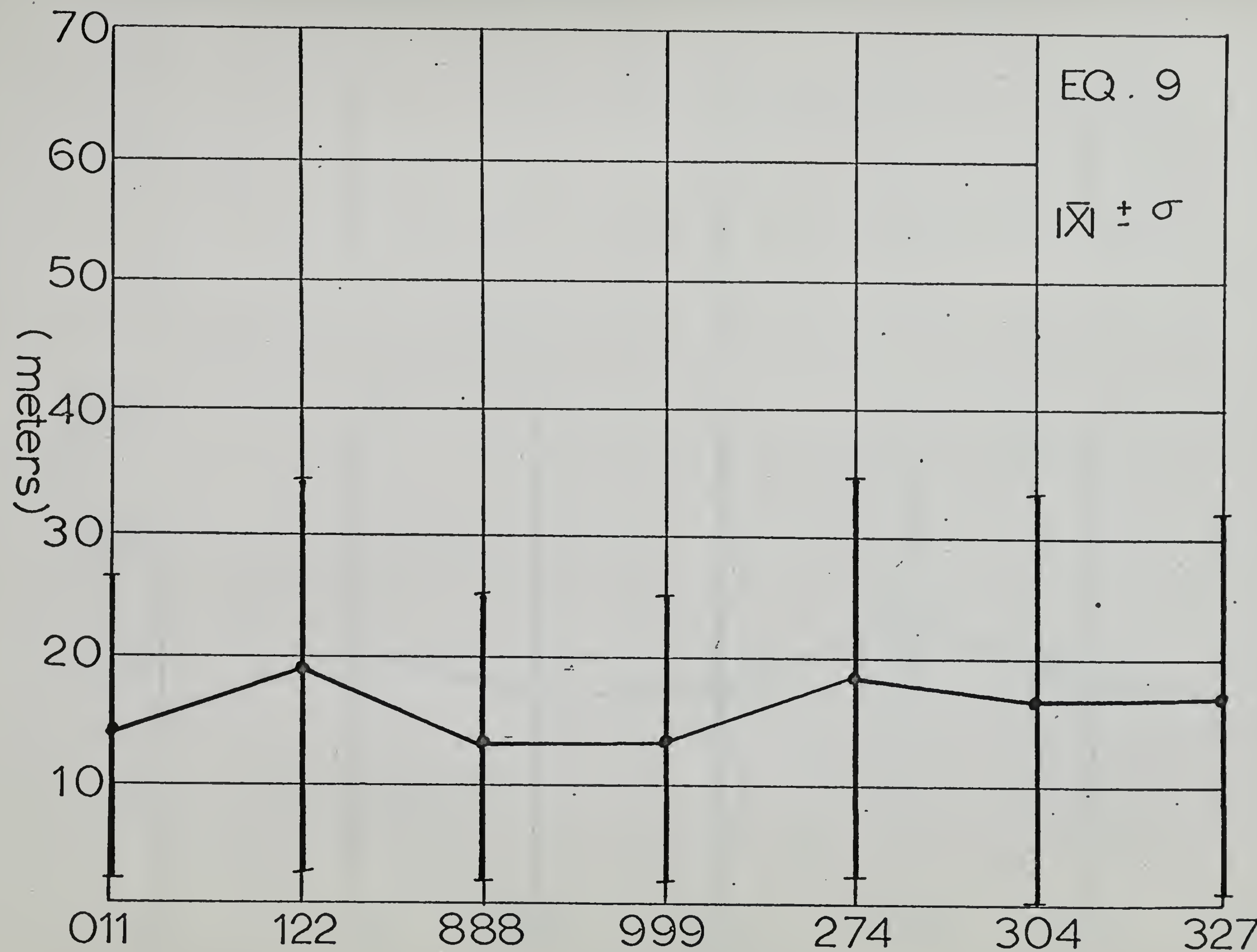
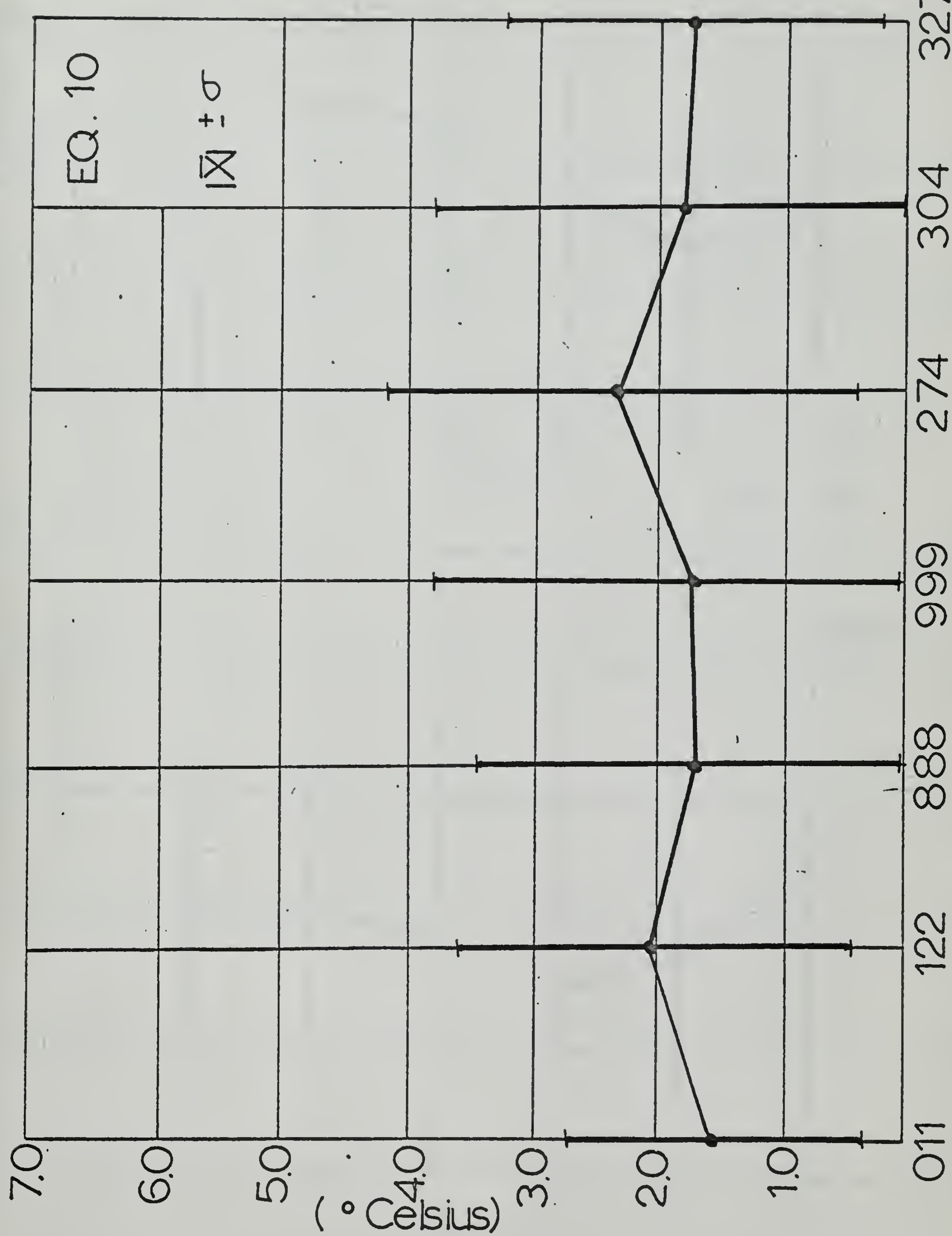

70
60
50
40
30
20
10
(meters)
EQ. 9
$|\bar{X}| \pm \sigma$
011
122
888
999
274
304
327

FIG. 2e



EQ. 10
$|\bar{X}| \pm \sigma$
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° Celsius)
011
122
888
999
274
304
327

FIG. 2f

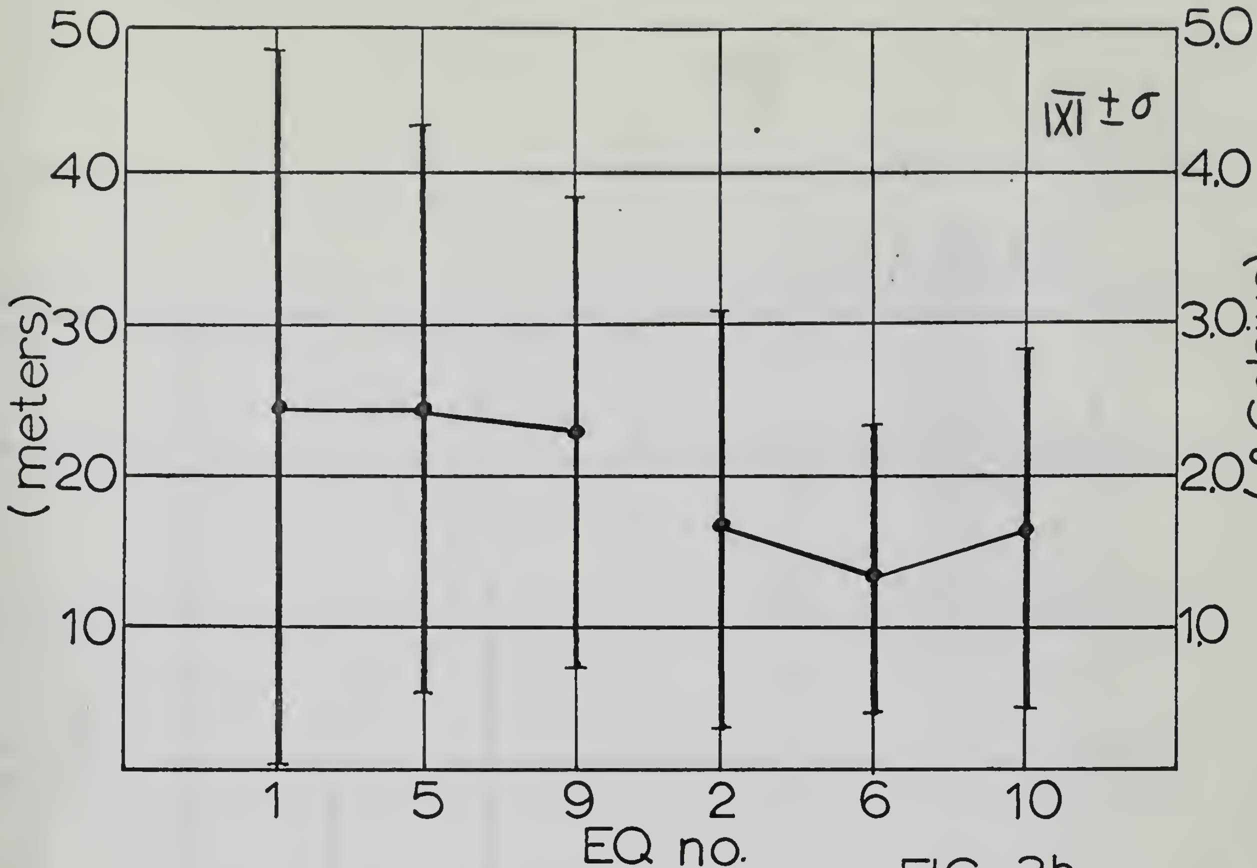

50
40
30
20
10
(meters)
5.0
4.0
3.0
2.0
1.0
(° Celsius)
|X| ± σ
1
5
9
2
6
10
EQ no.

FIG. 3b

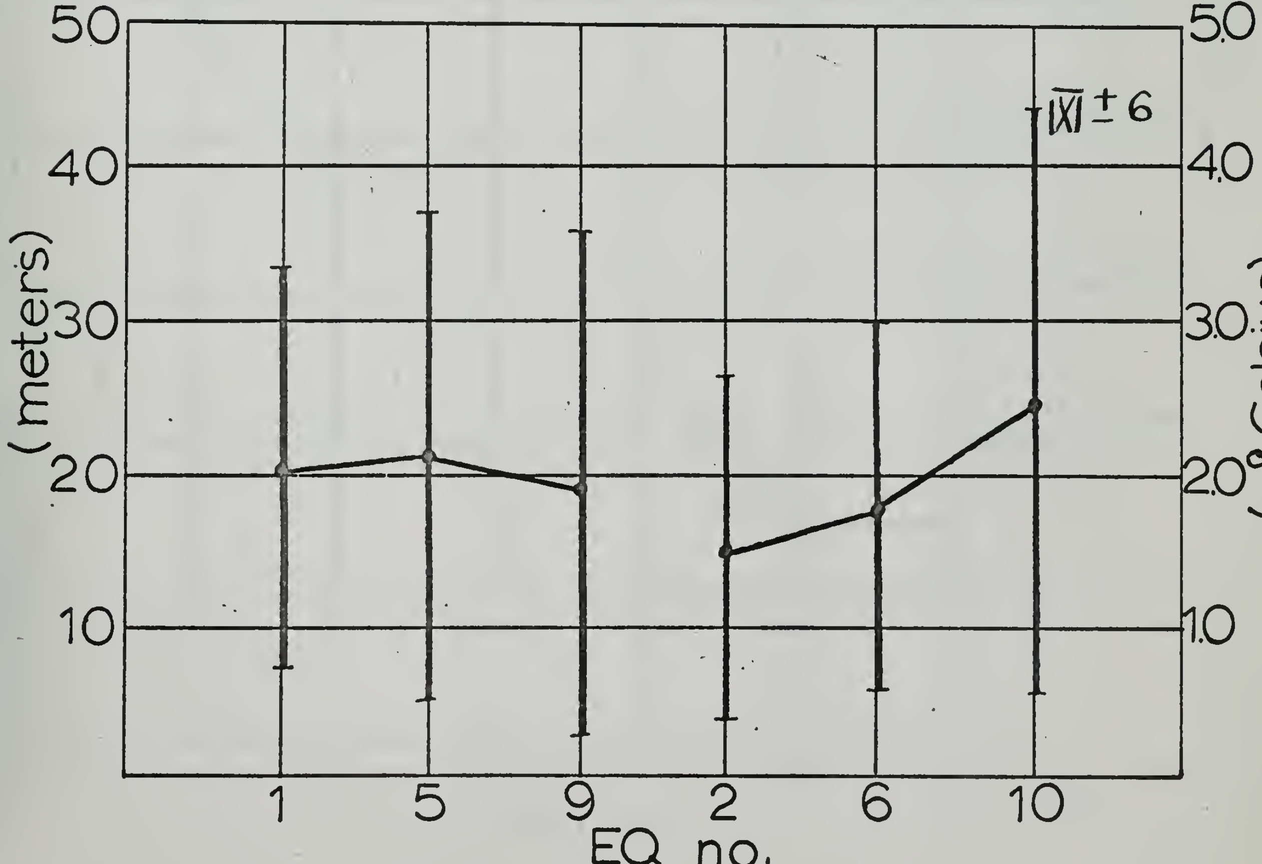
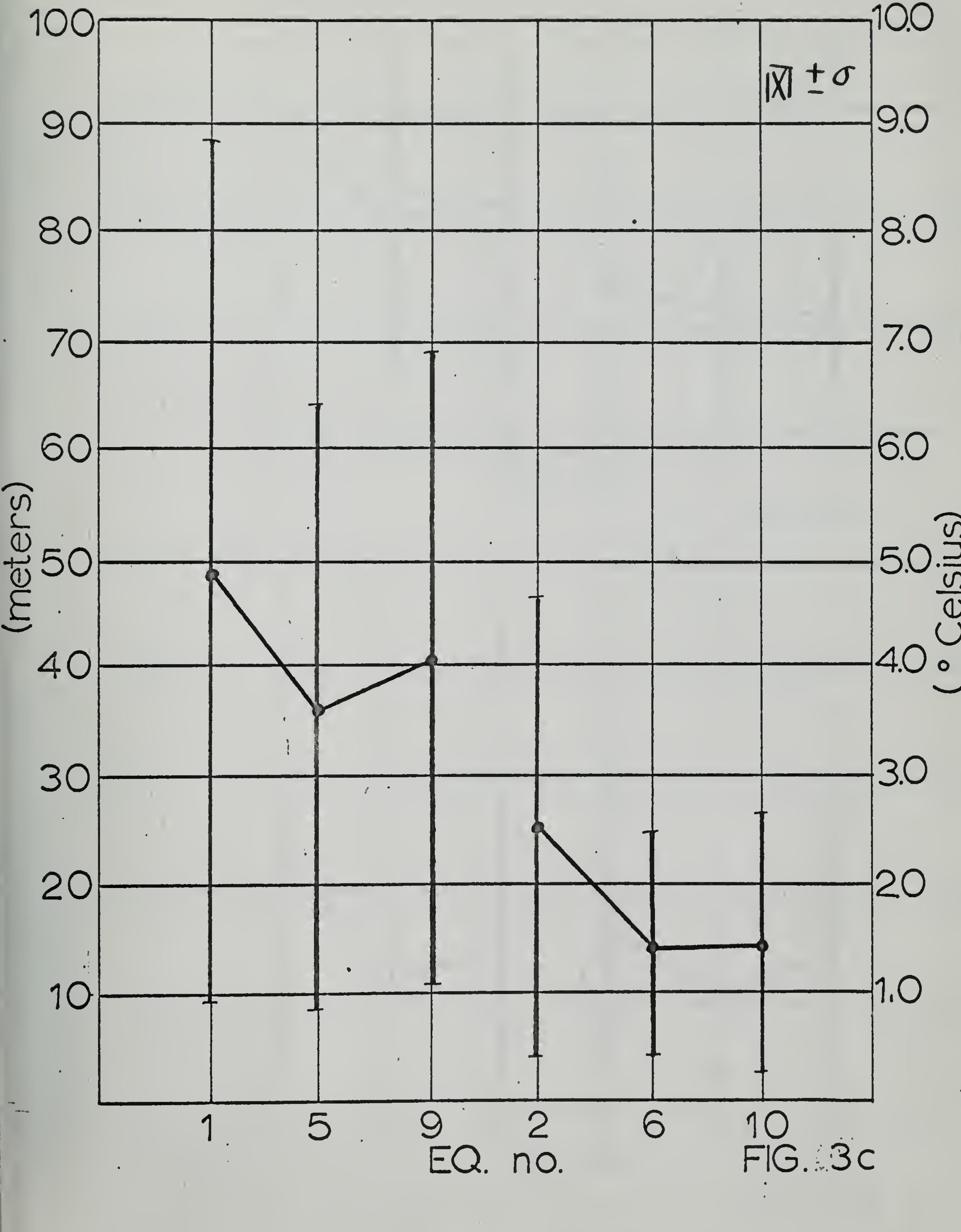
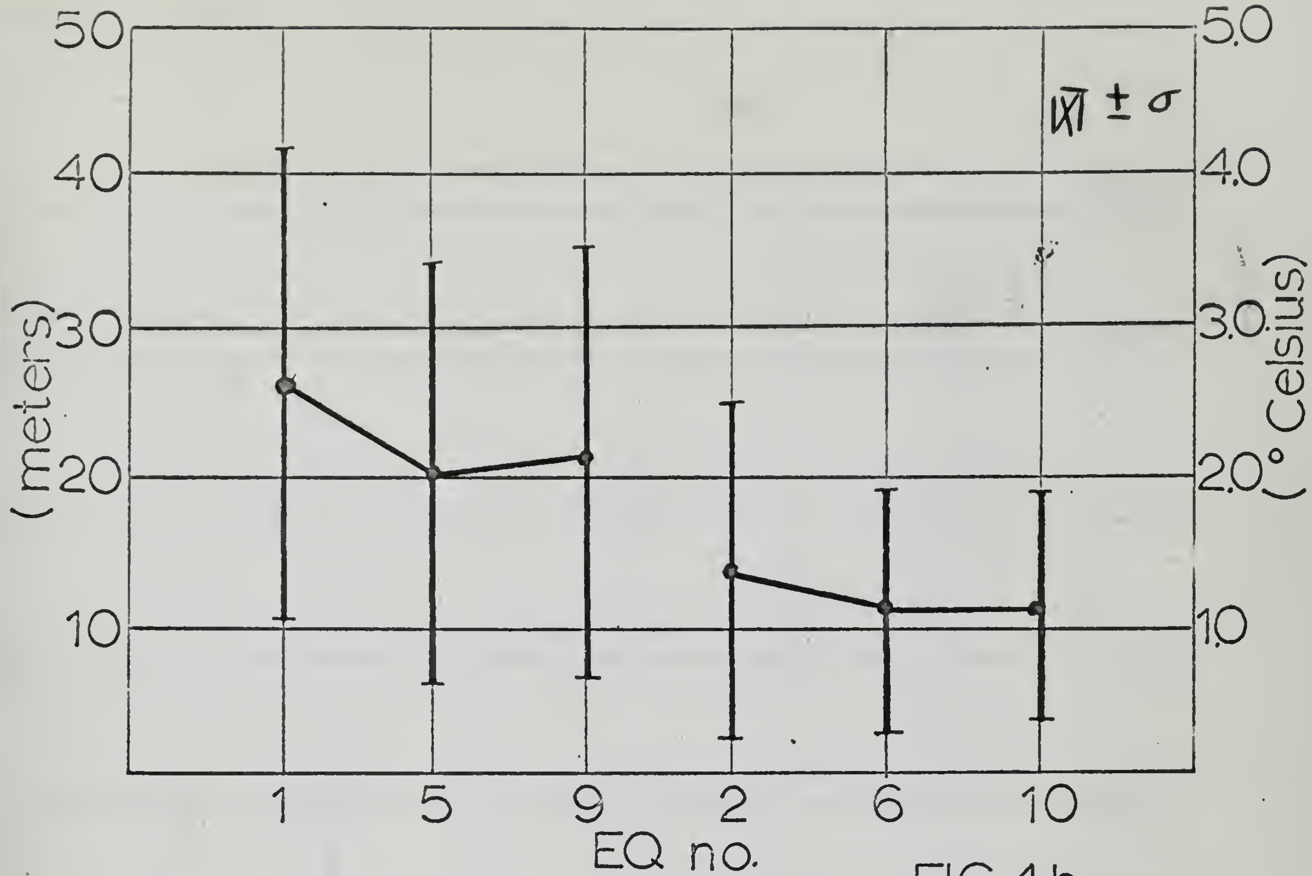

50
40
30
20
10
(meters)
5.0
4.0
3.0
2.0
1.0
(° Celsius)
|X| ± 6
1
5
9
2
6
10
EQ no.

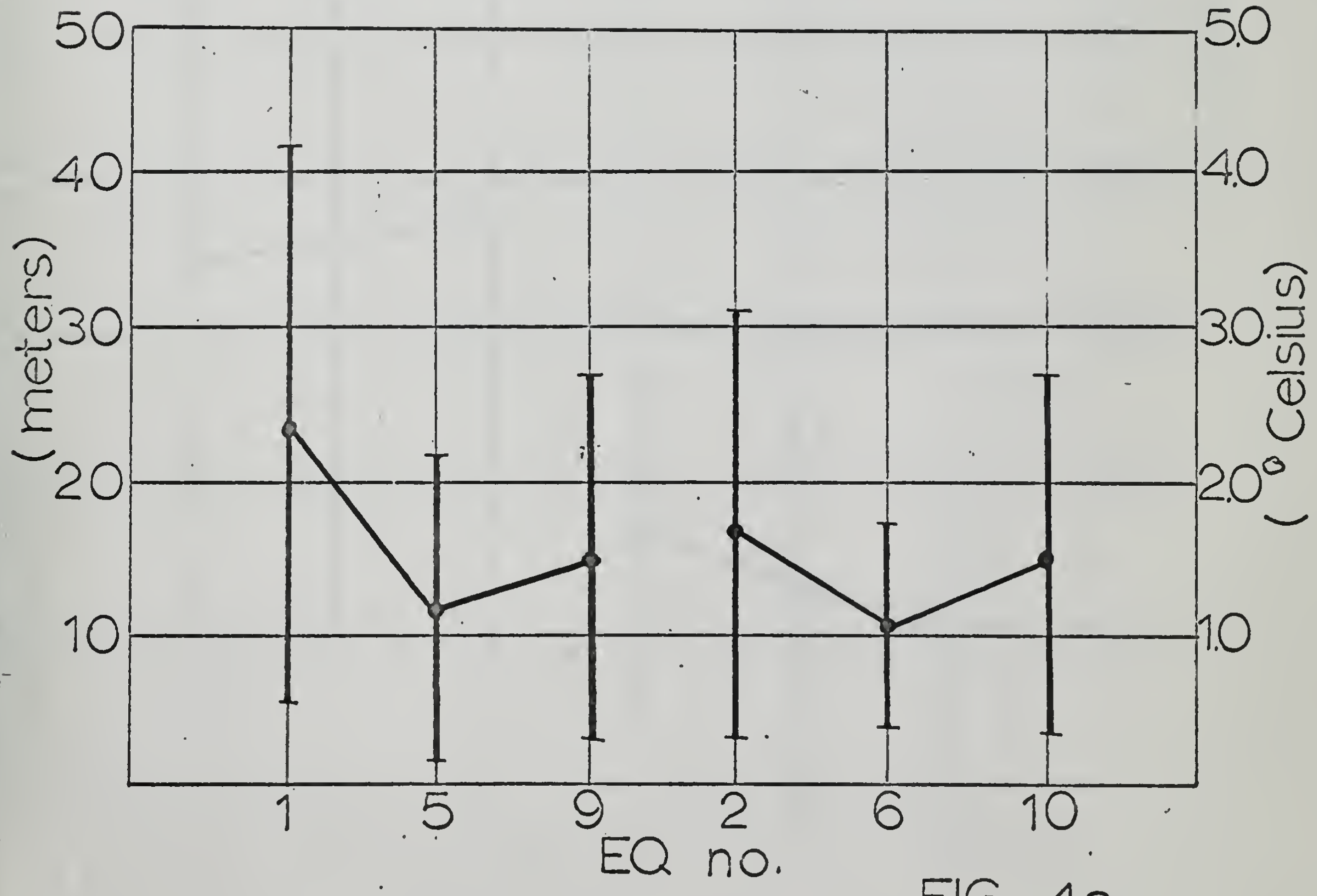
FIG. 3a


100
90
80
70
60
50
40
30
20
10
(meters)
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
(° Celsius)
|X̄| ± σ
1
5
9
2
6
10
EQ. no.
FIG. 3c



50
40
30
20
10
(meters)
5.0
4.0
3.0
2.0
1.0
(° Celsius)
$\overline{|X|} \pm \sigma$
1
5
9
2
6
10
EQ no.

FIG.4 b



50
40
30
20
10
(meters)
5.0
4.0
3.0
2.0
1.0
(° Celsius)
1
5
9
2
6
10
EQ no.

FIG. 4a

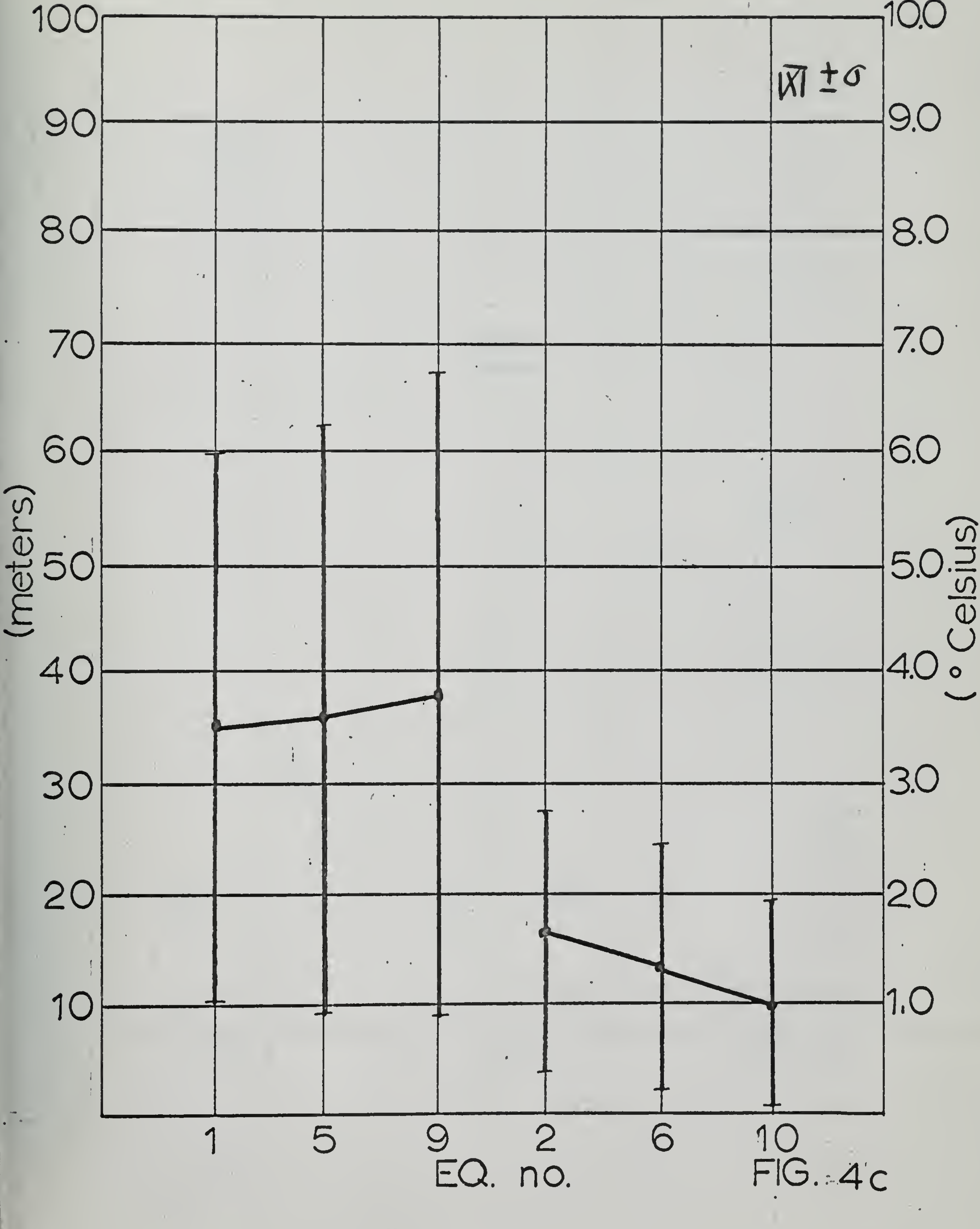

$|\bar{X}| \pm \sigma$
(meters)
(° Celsius)
100
90
80
70
60
50
40
30
20
10
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
1
5
9
2
6
10
EQ. no.

FIG. 4c

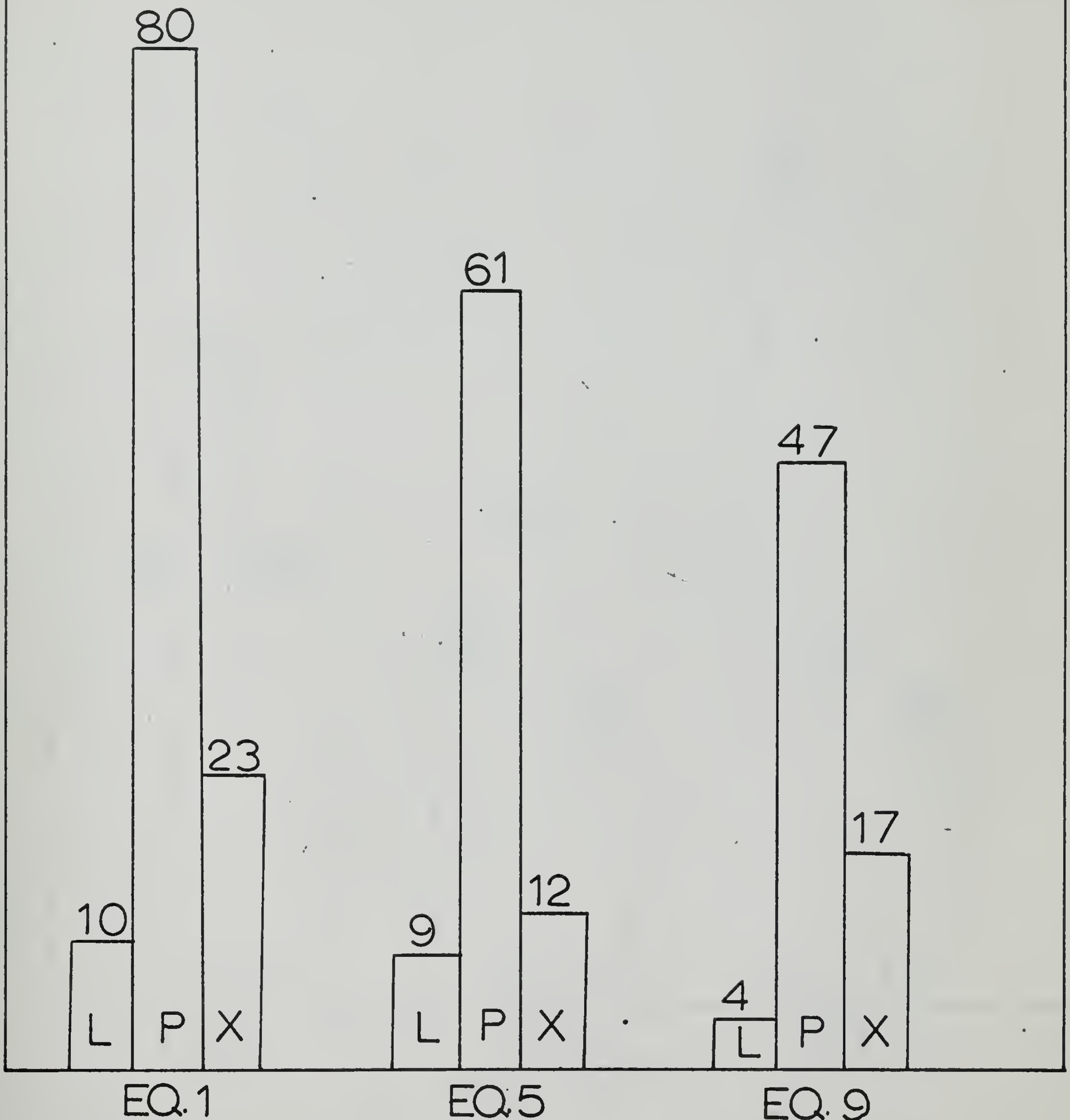


FIG. 5a

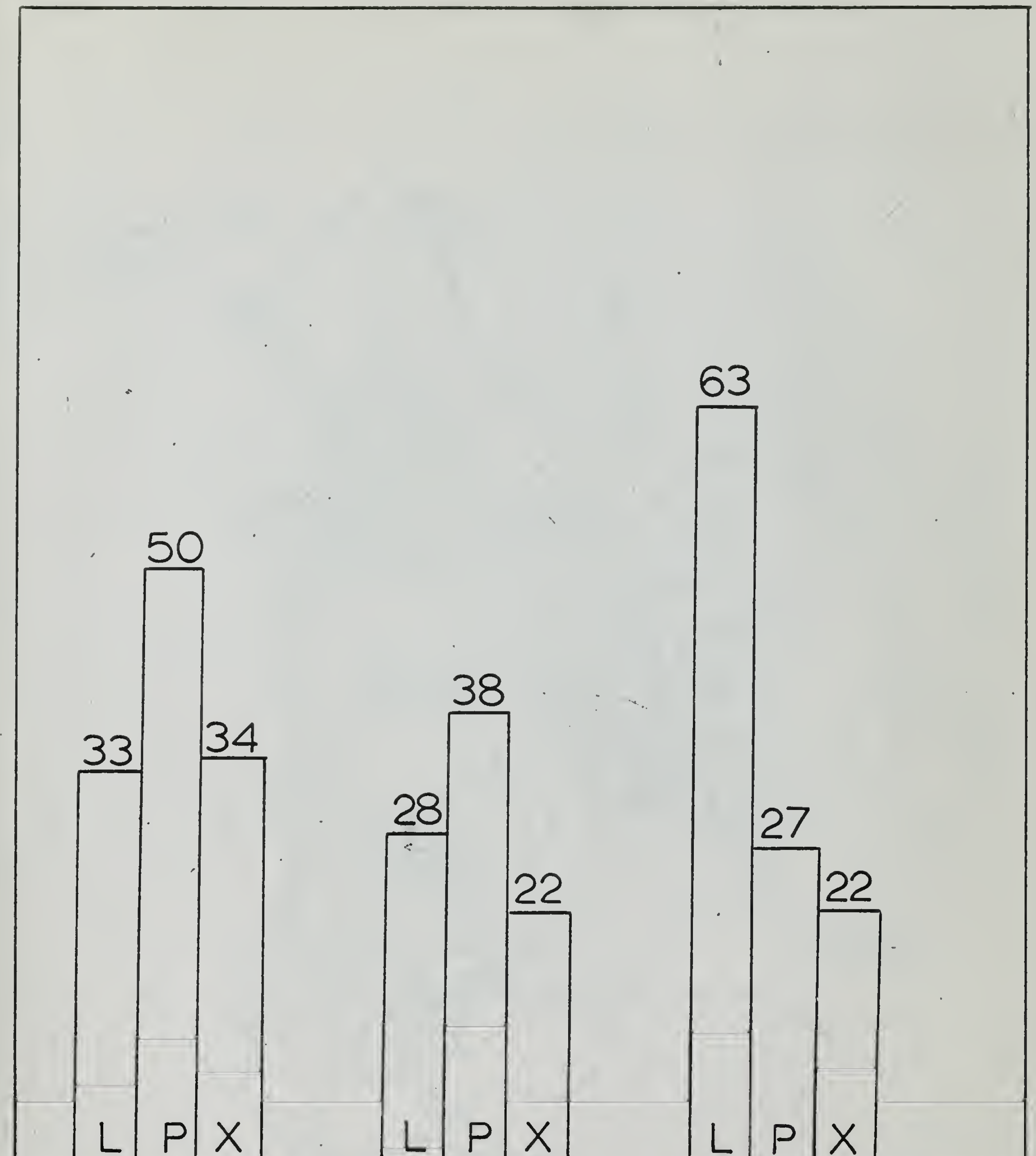


FIG. 5b

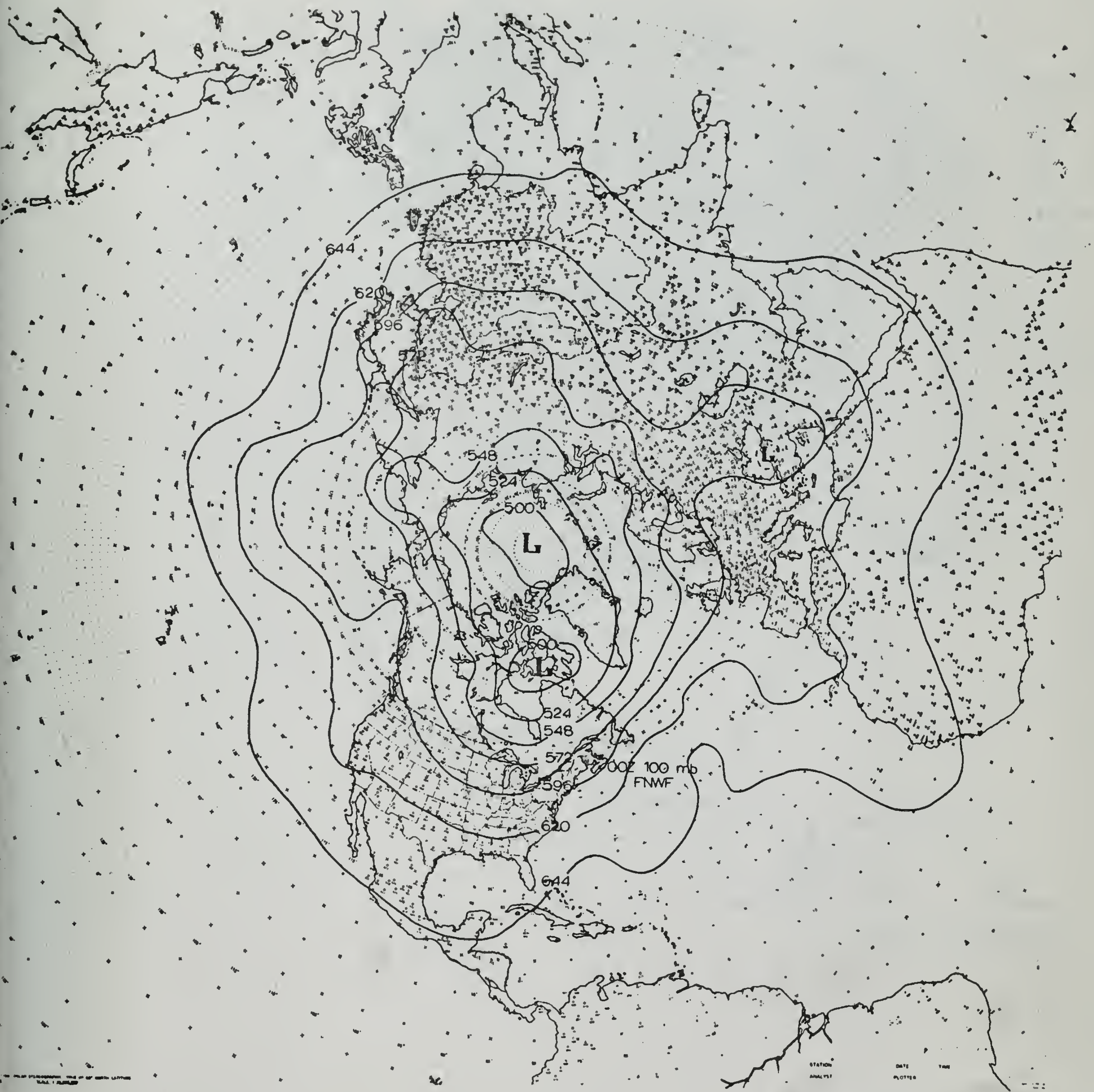


Fig. 6

500 = 15000 m

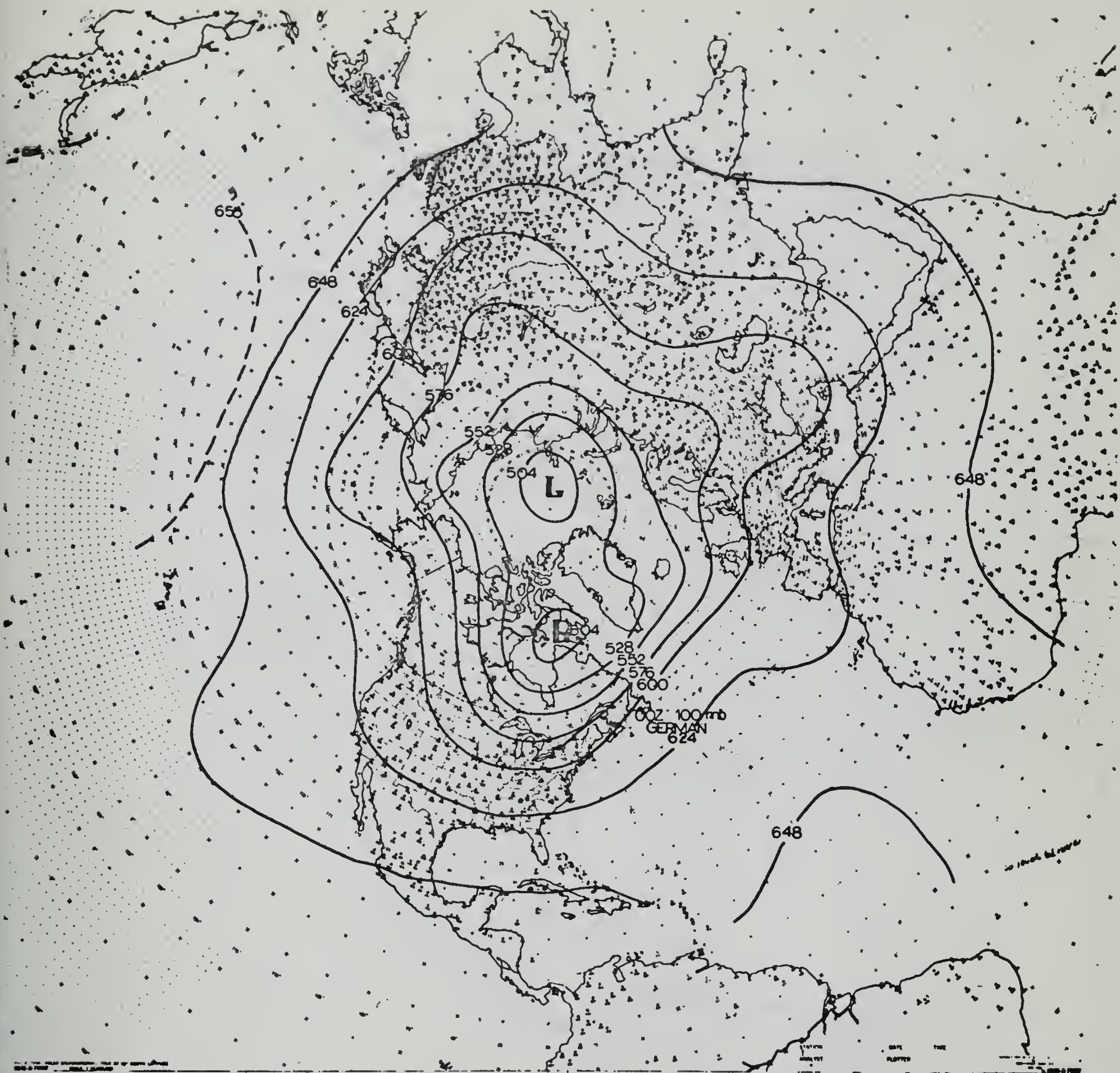
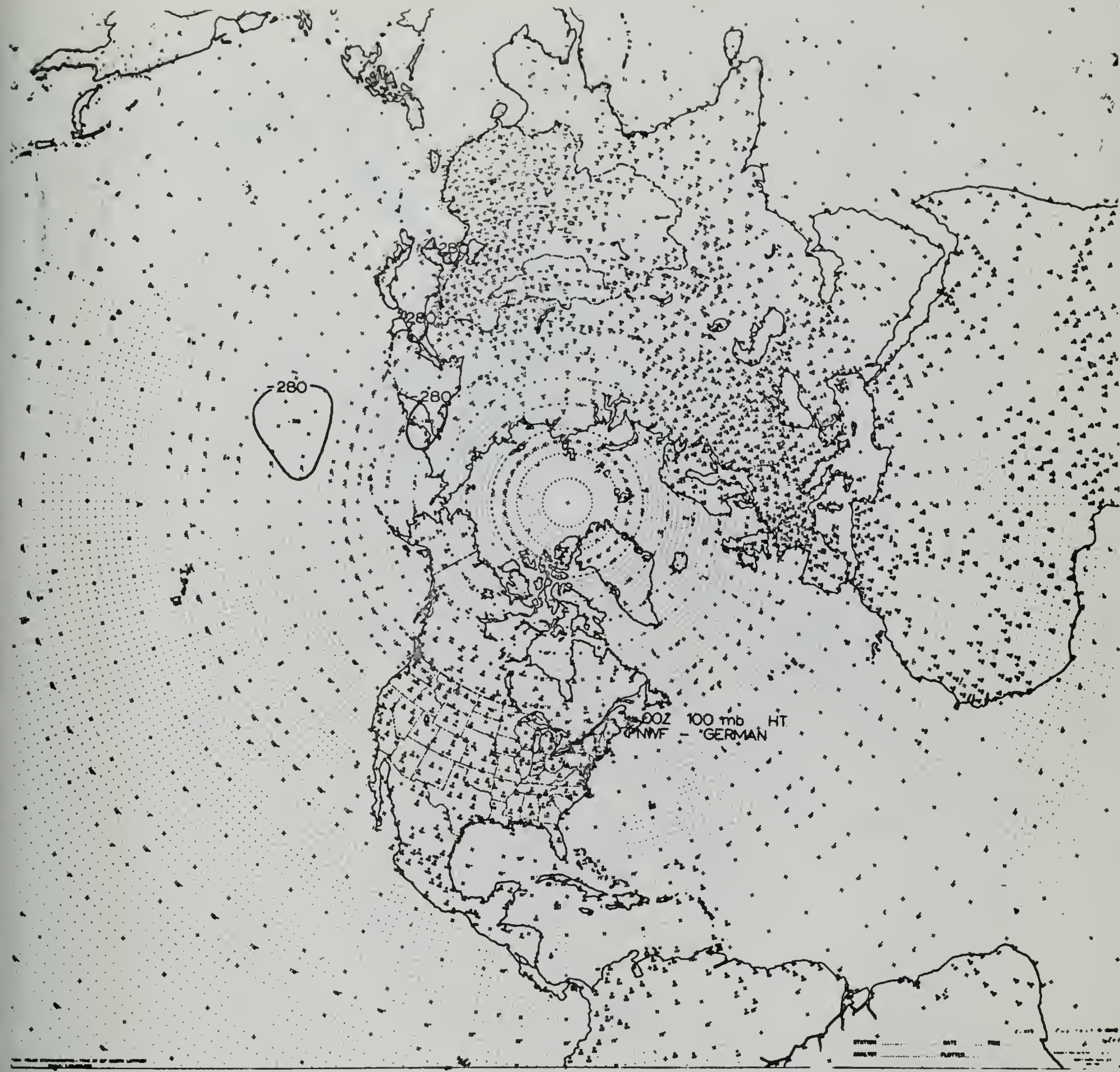


Fig. 7

504 = 15040 m



ht. in meters

Fig. 8

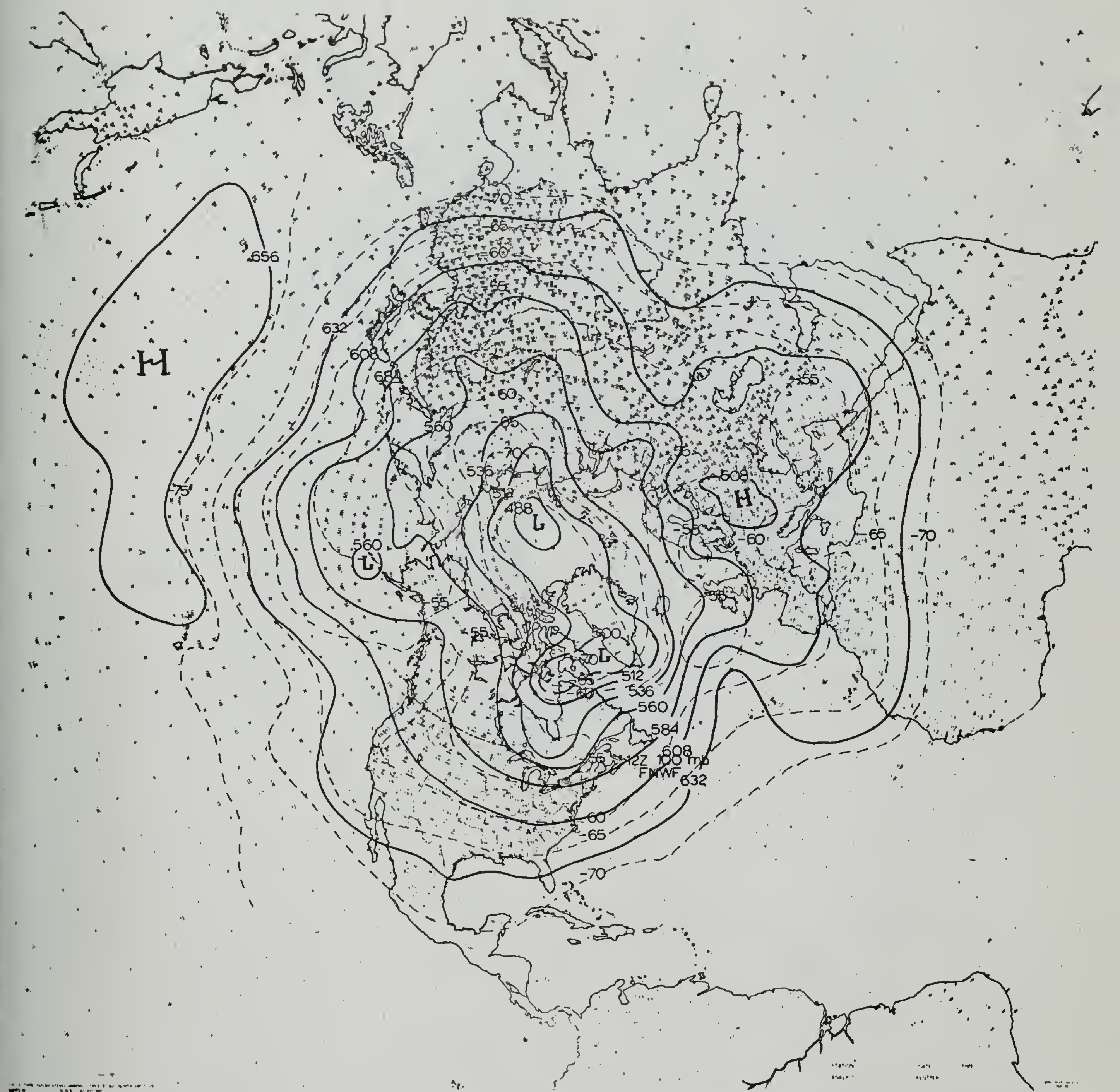


Fig 9

ht. 488 = 14880 m
temp. -70 = -70C

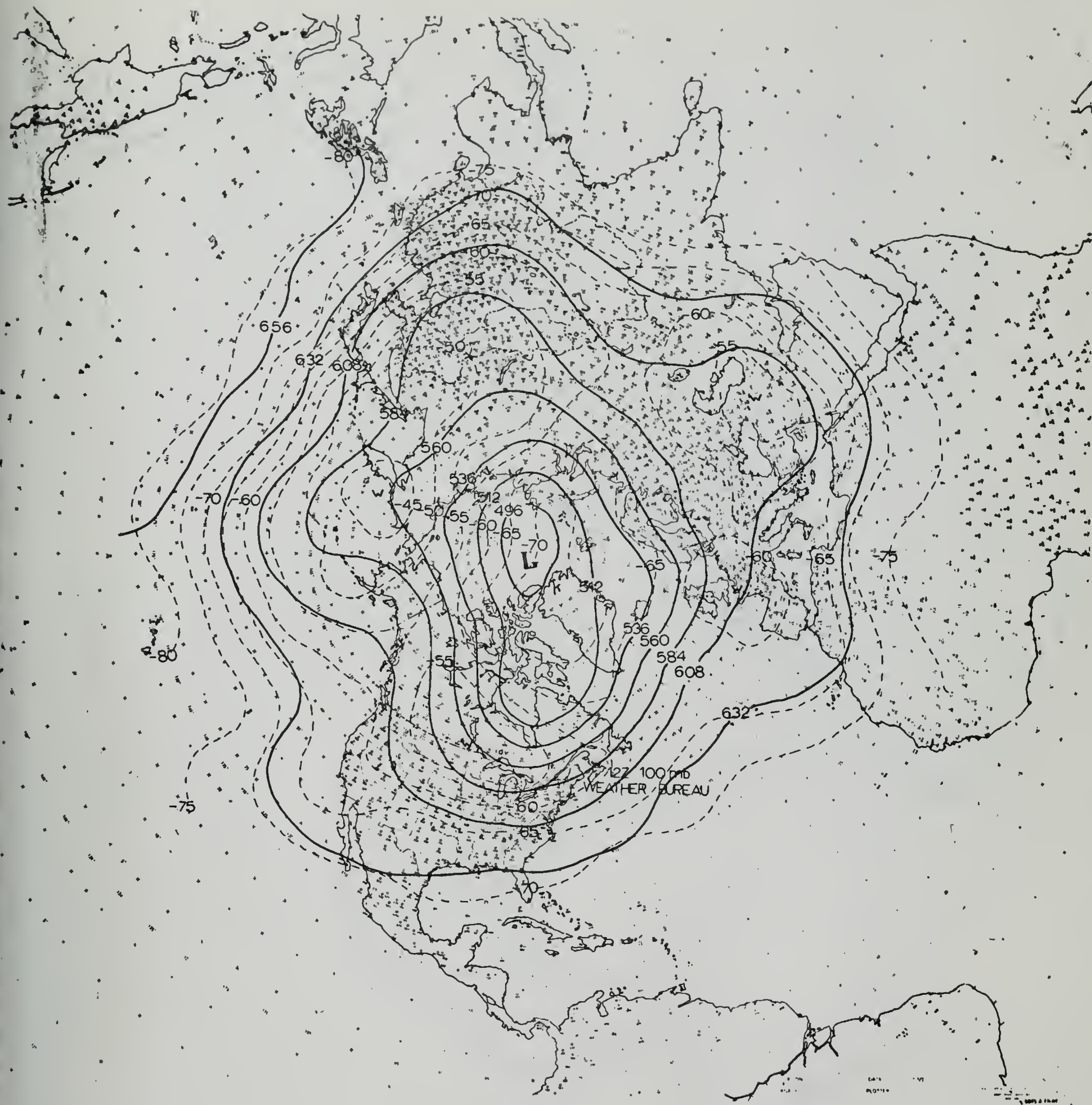


Fig. 10

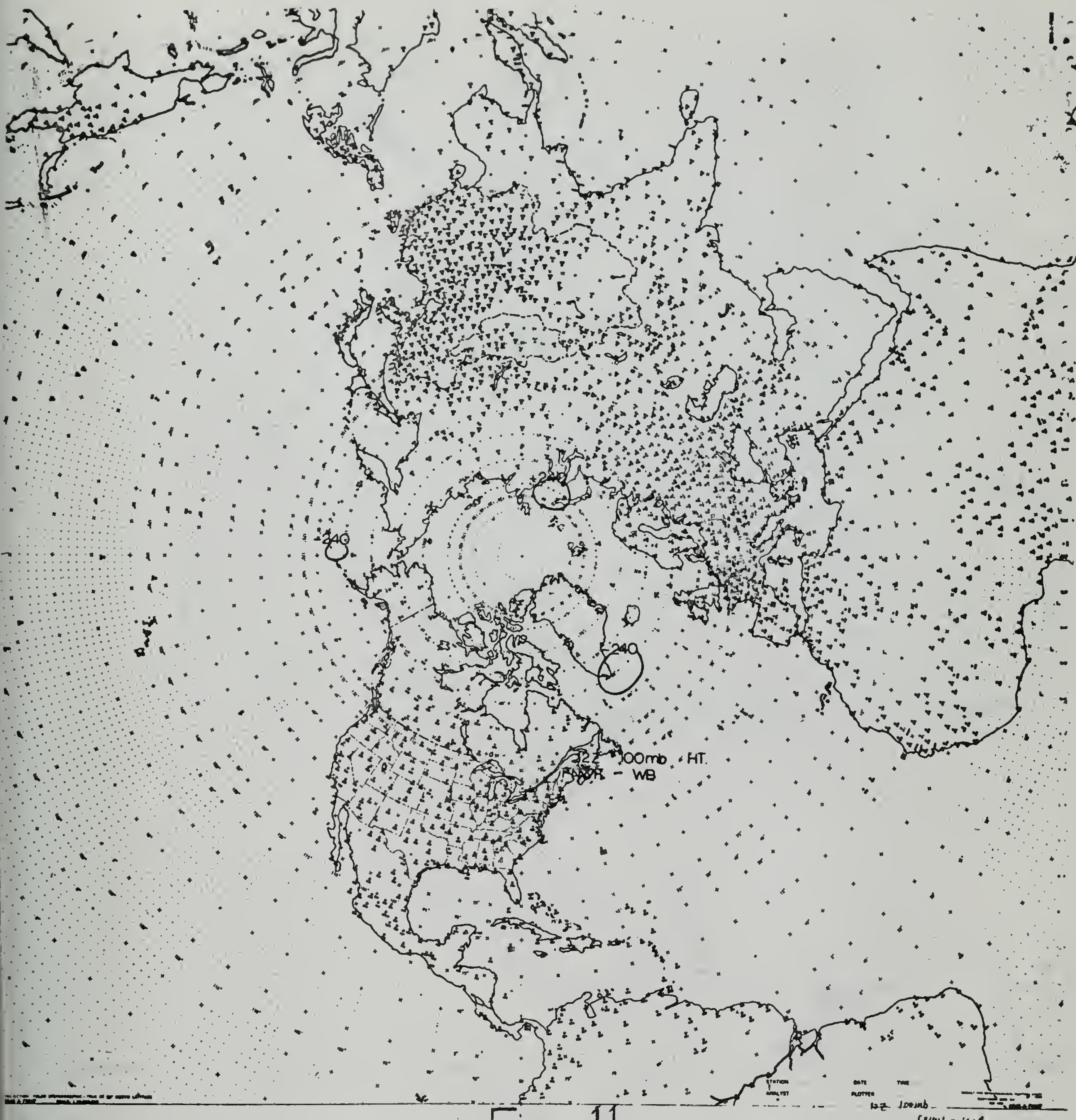


Fig. 11

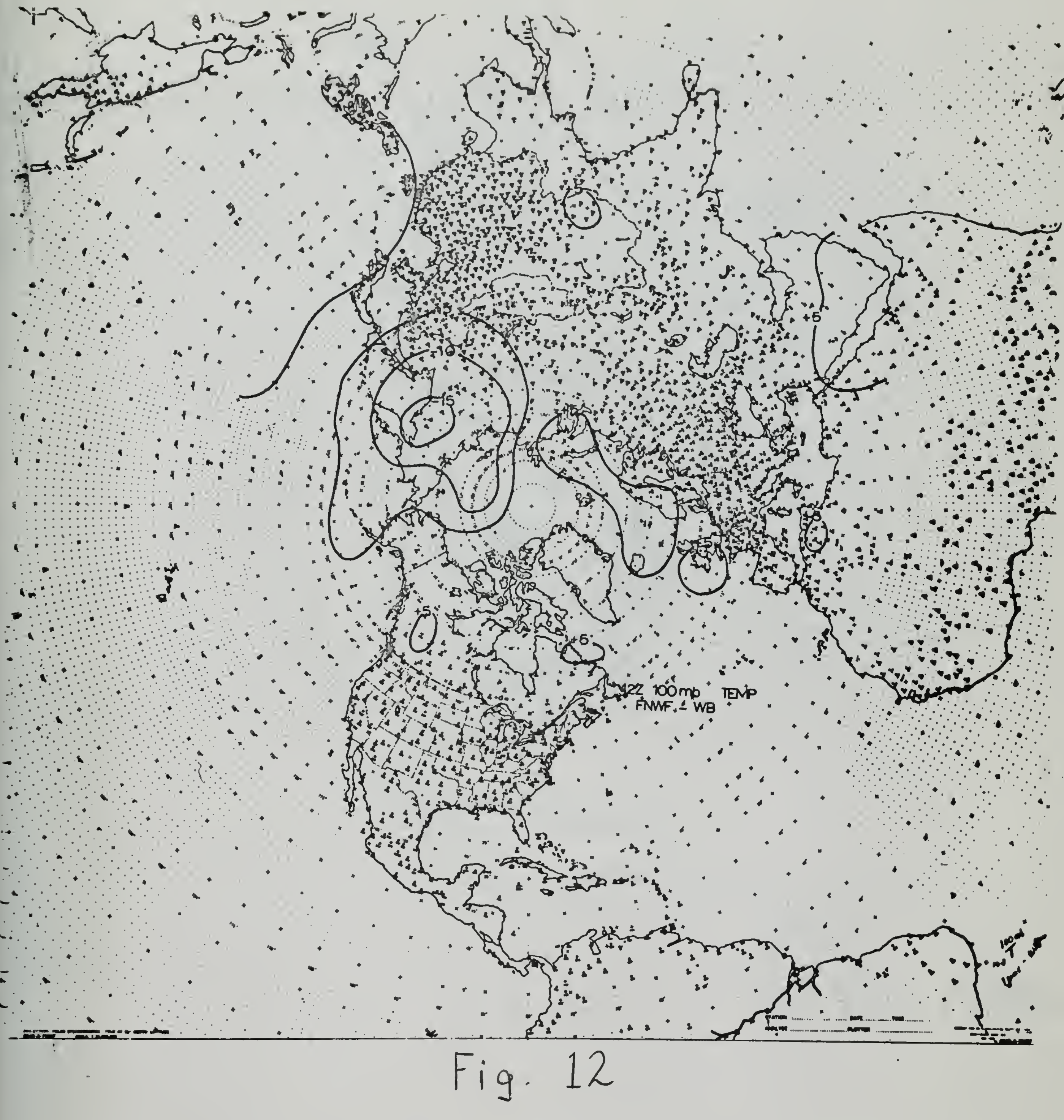


Fig. 12

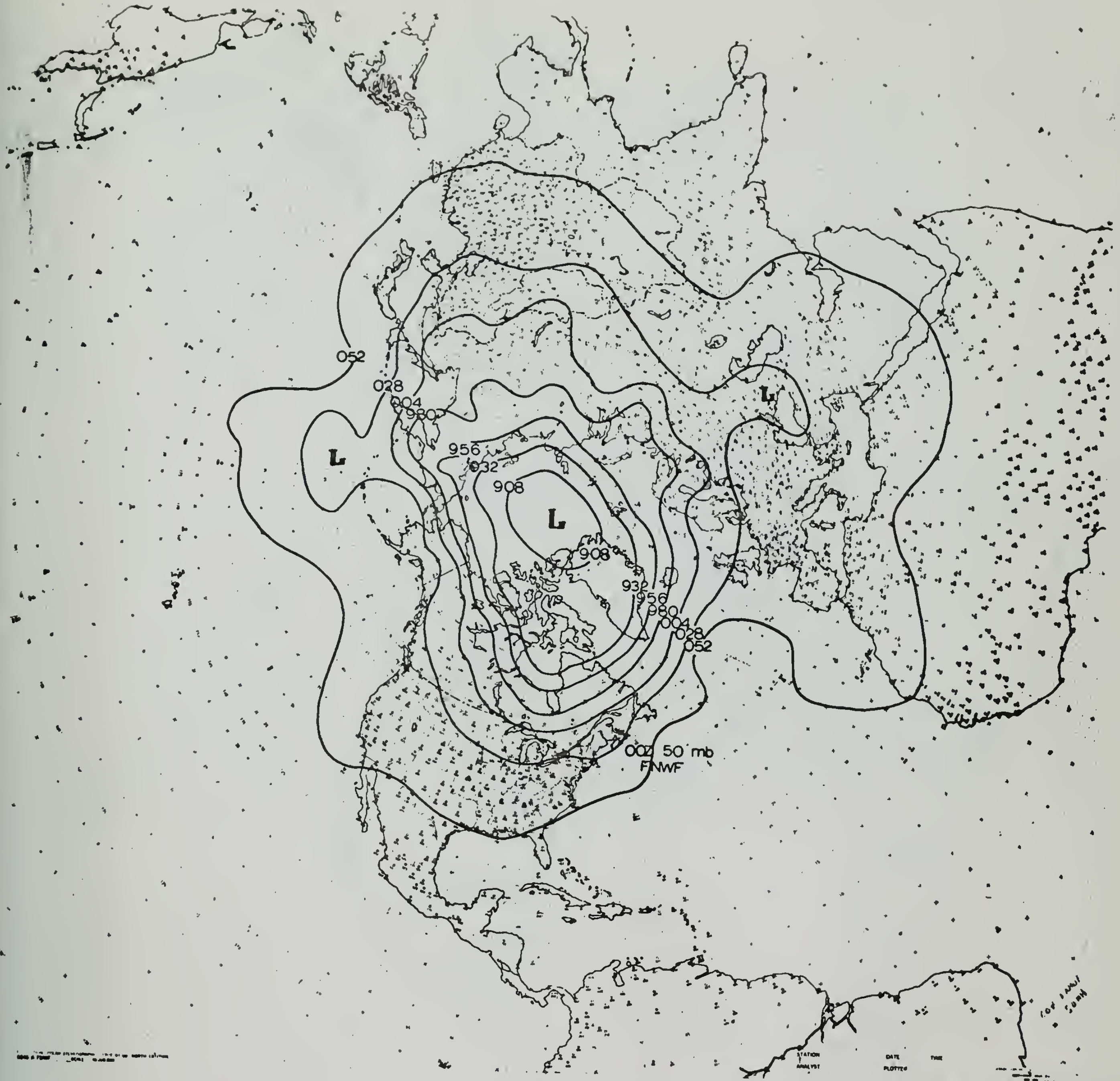


Fig. 13 ht. 908 = 19080m

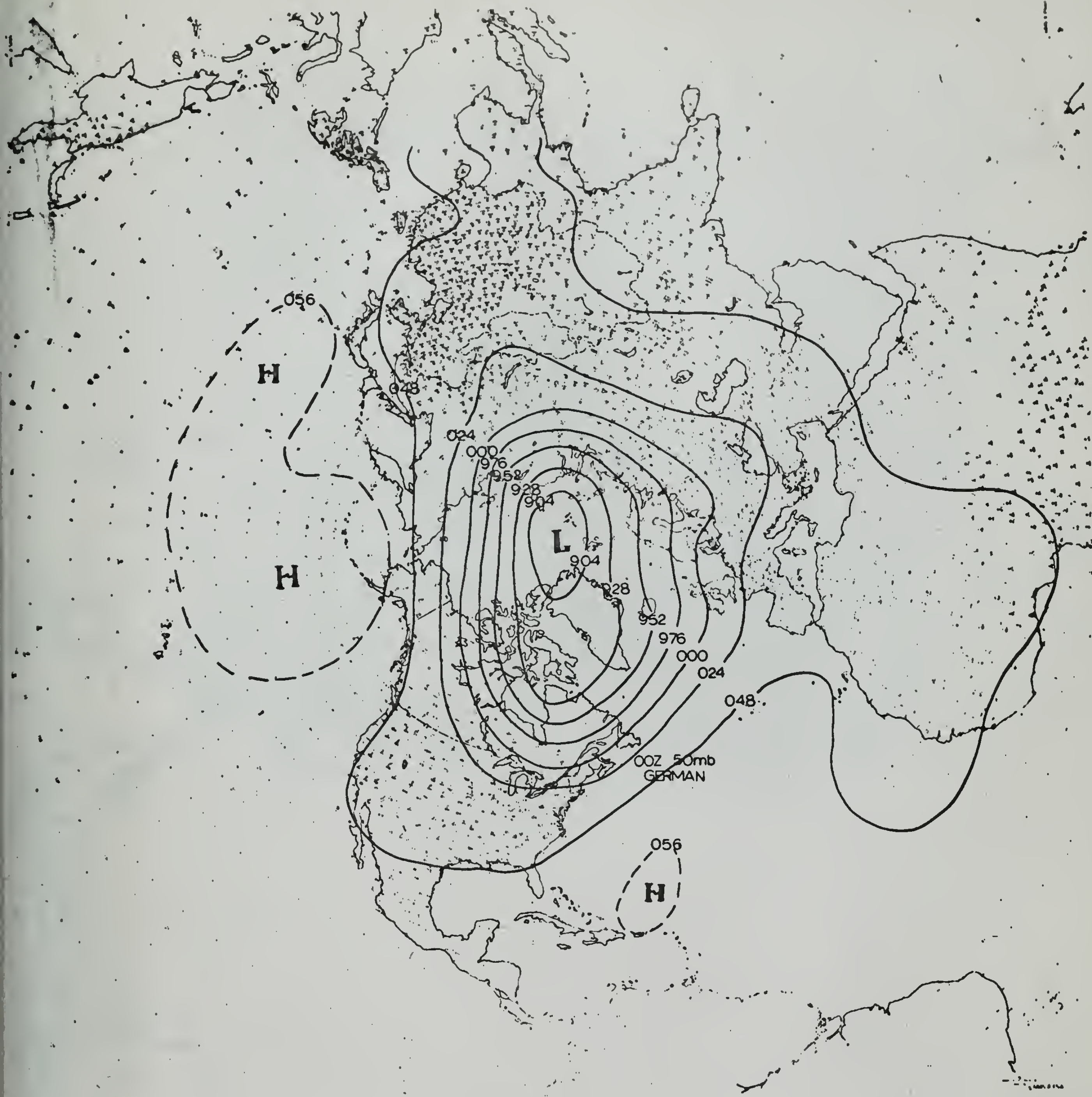


Fig 14

ht. 904 = 19040 m

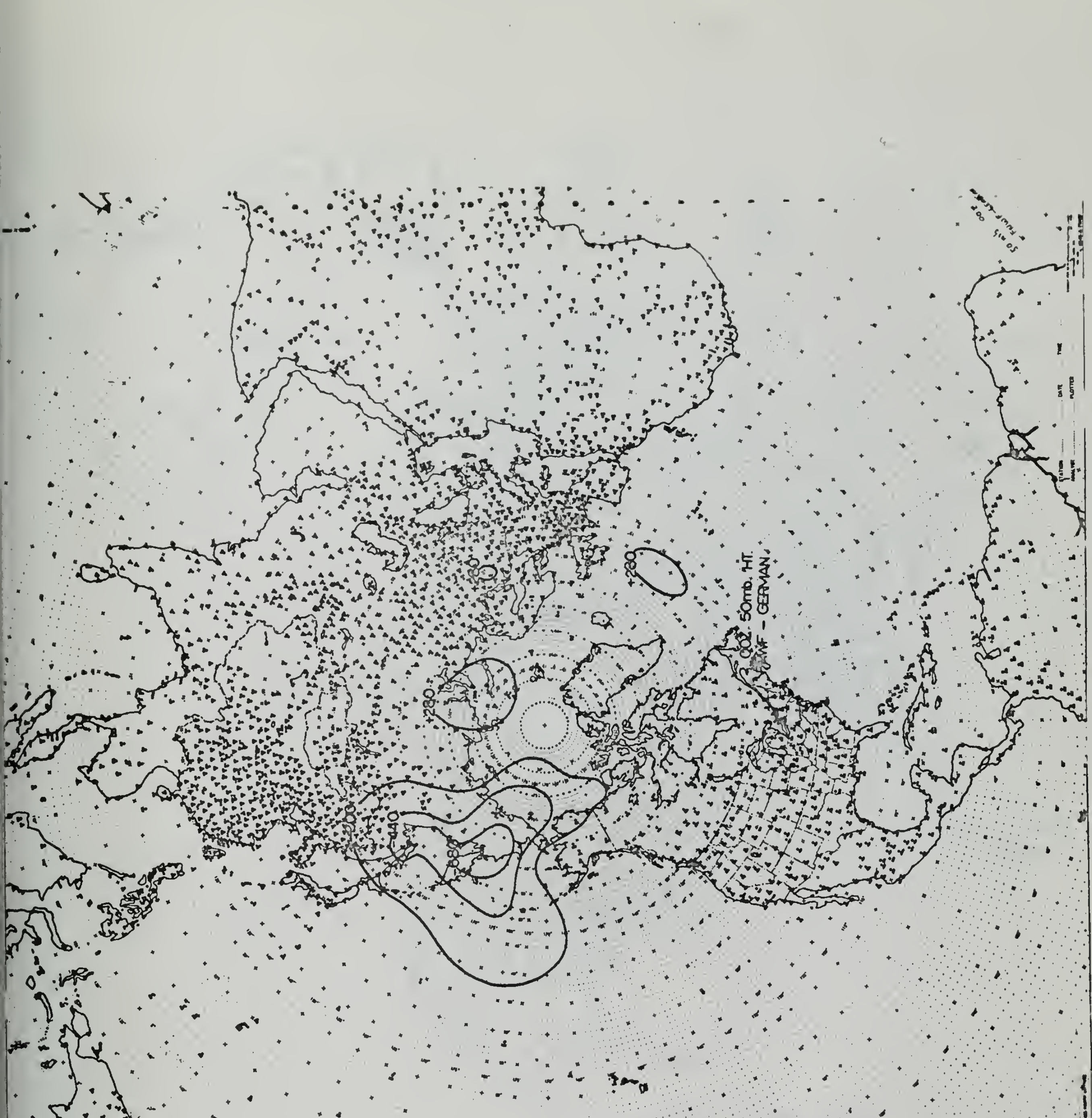


Fig 15

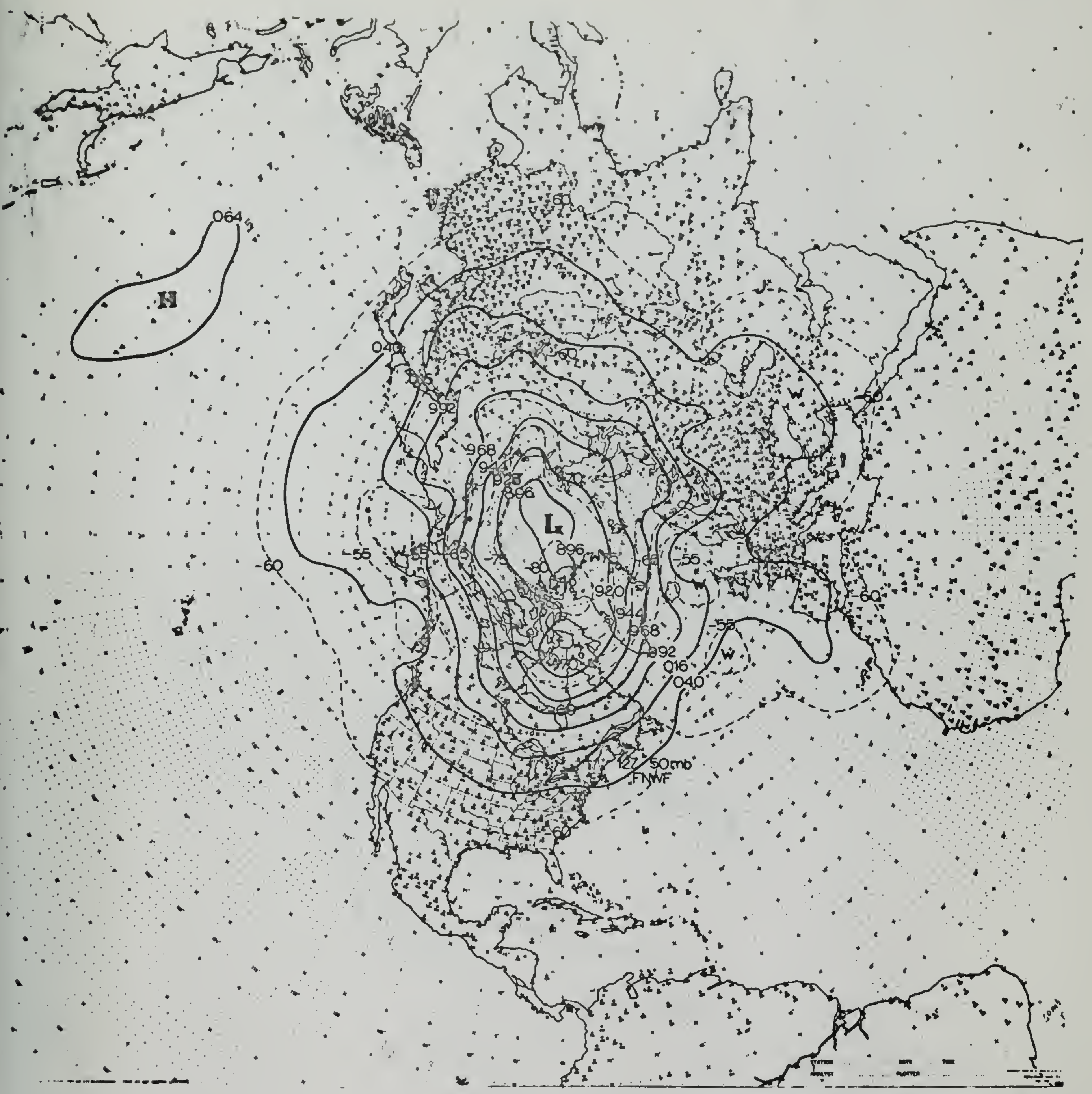


Fig. 16   ht 896 = 18960 m
temp -80 = -80C

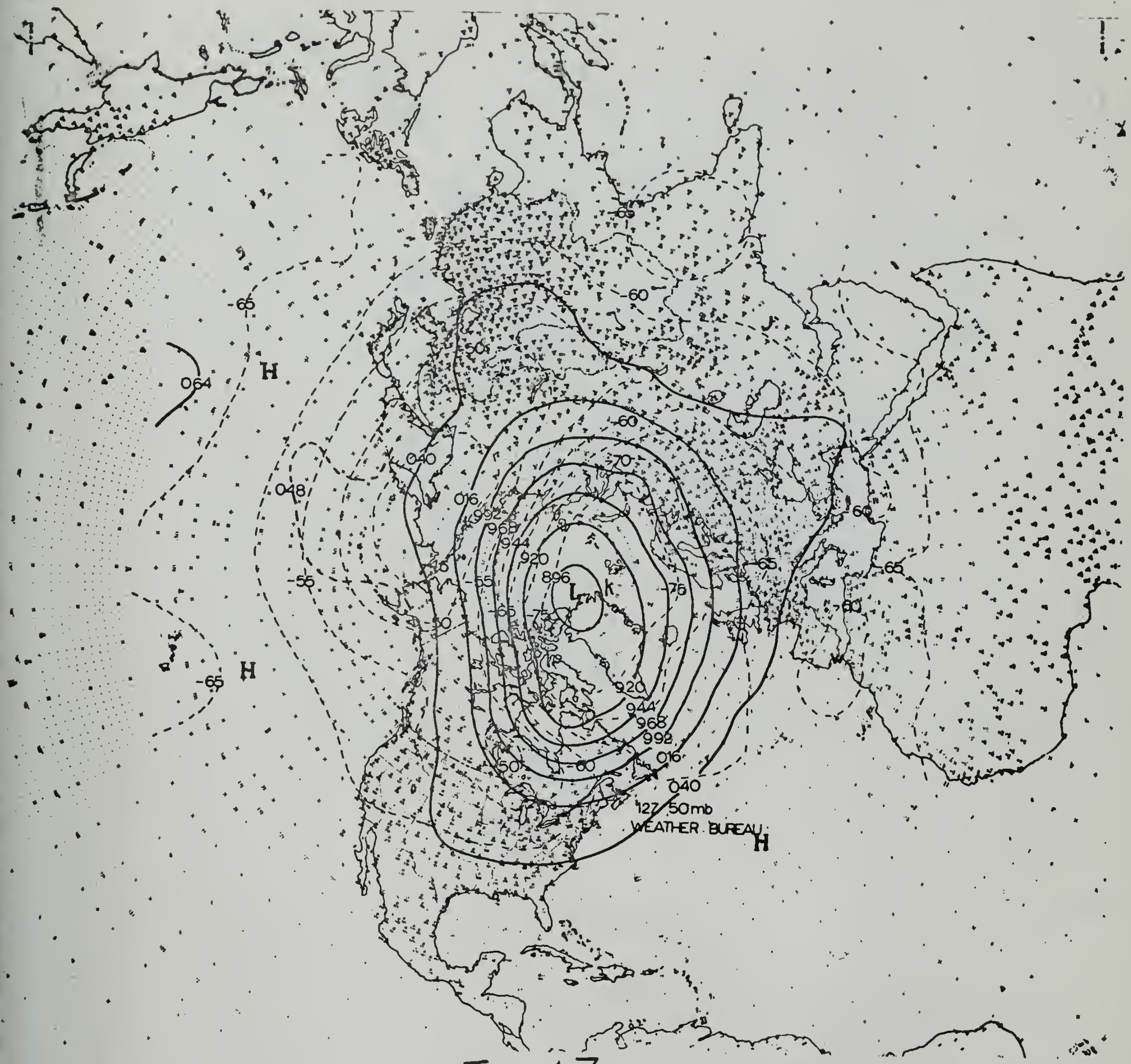


Fig 17

ht 896 = 18960 m

temp -75 = -75 C

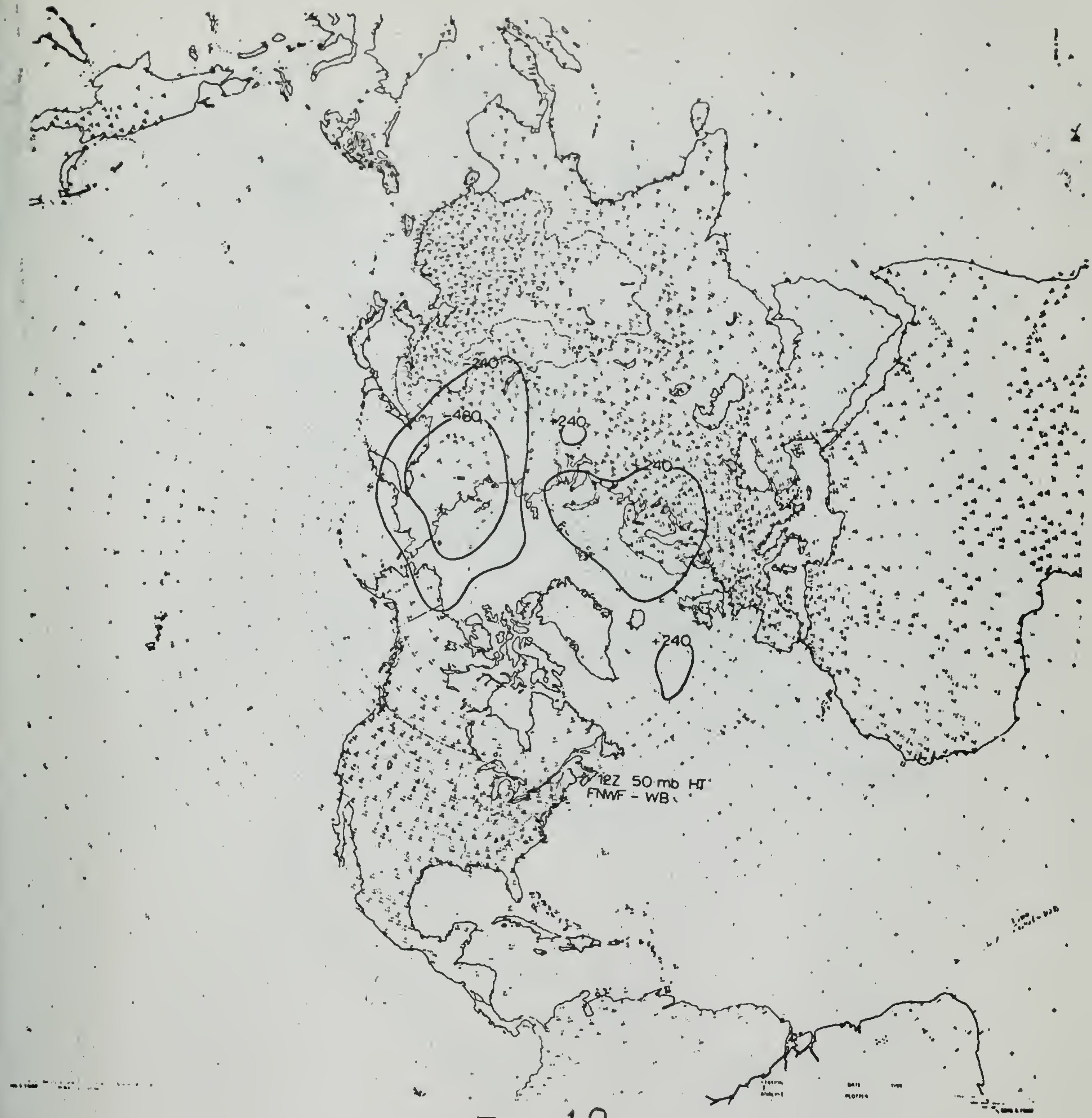


Fig. 18

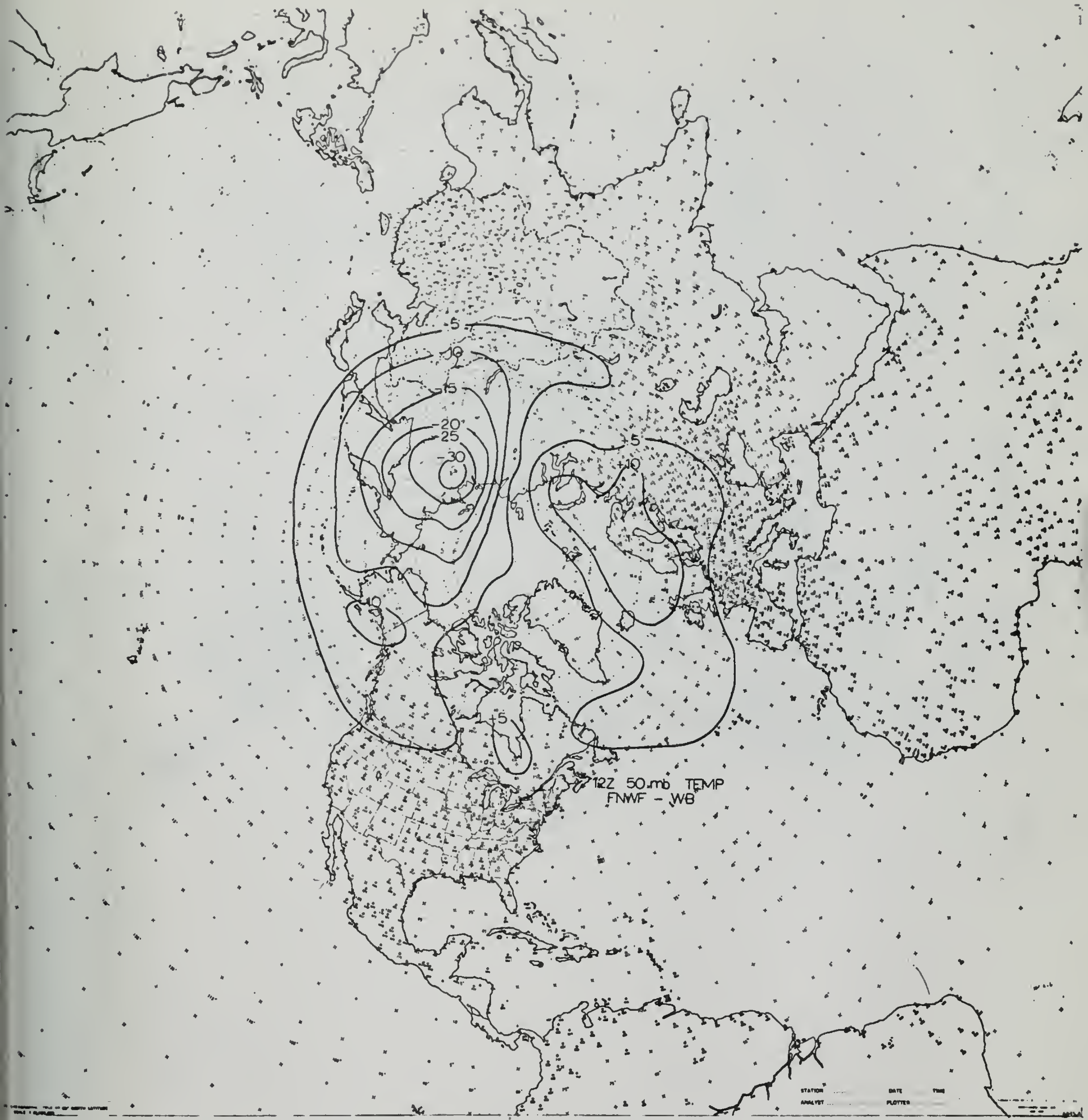


Fig 19

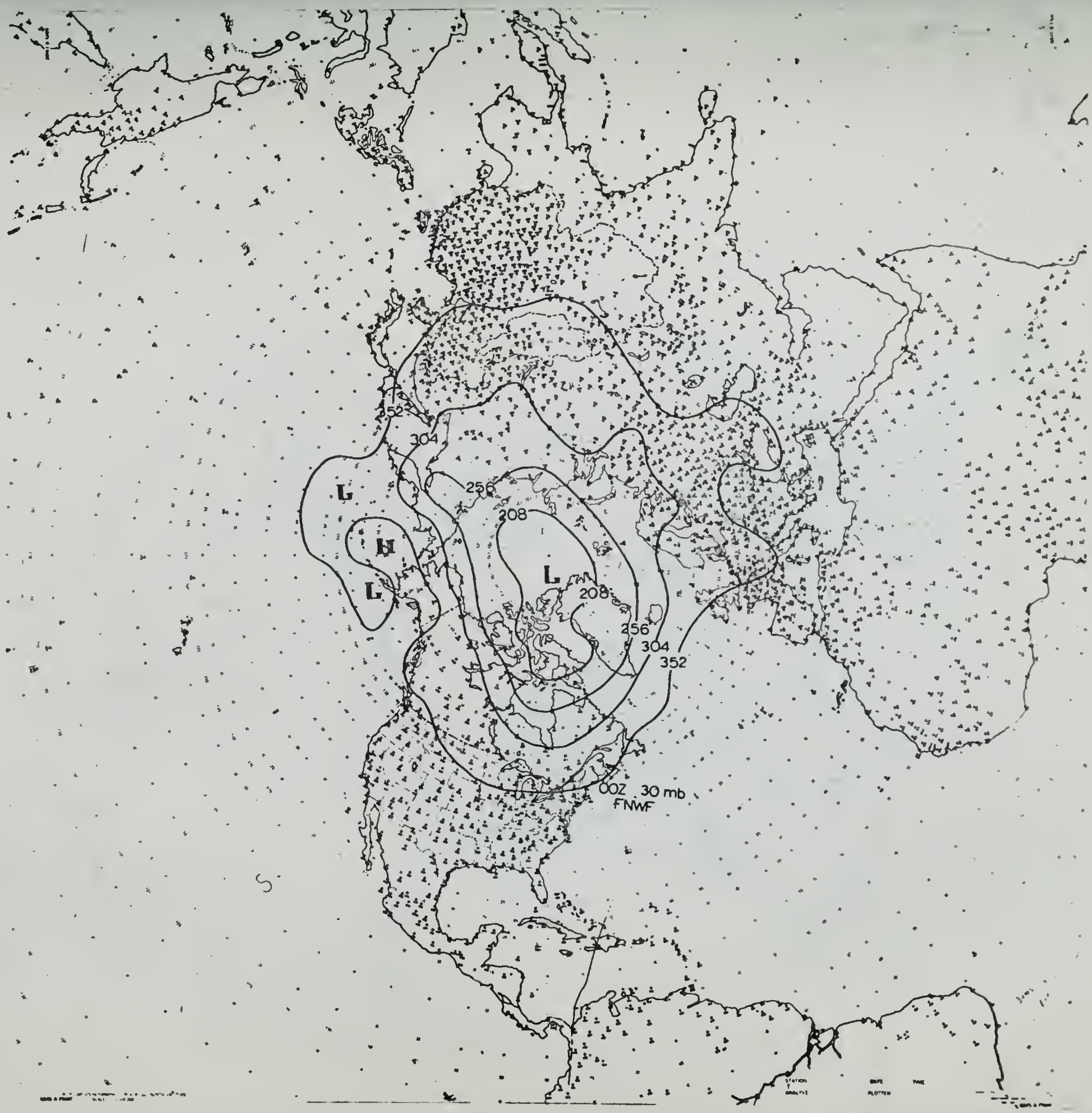


Fig 20

ht. 208 = 22080 m

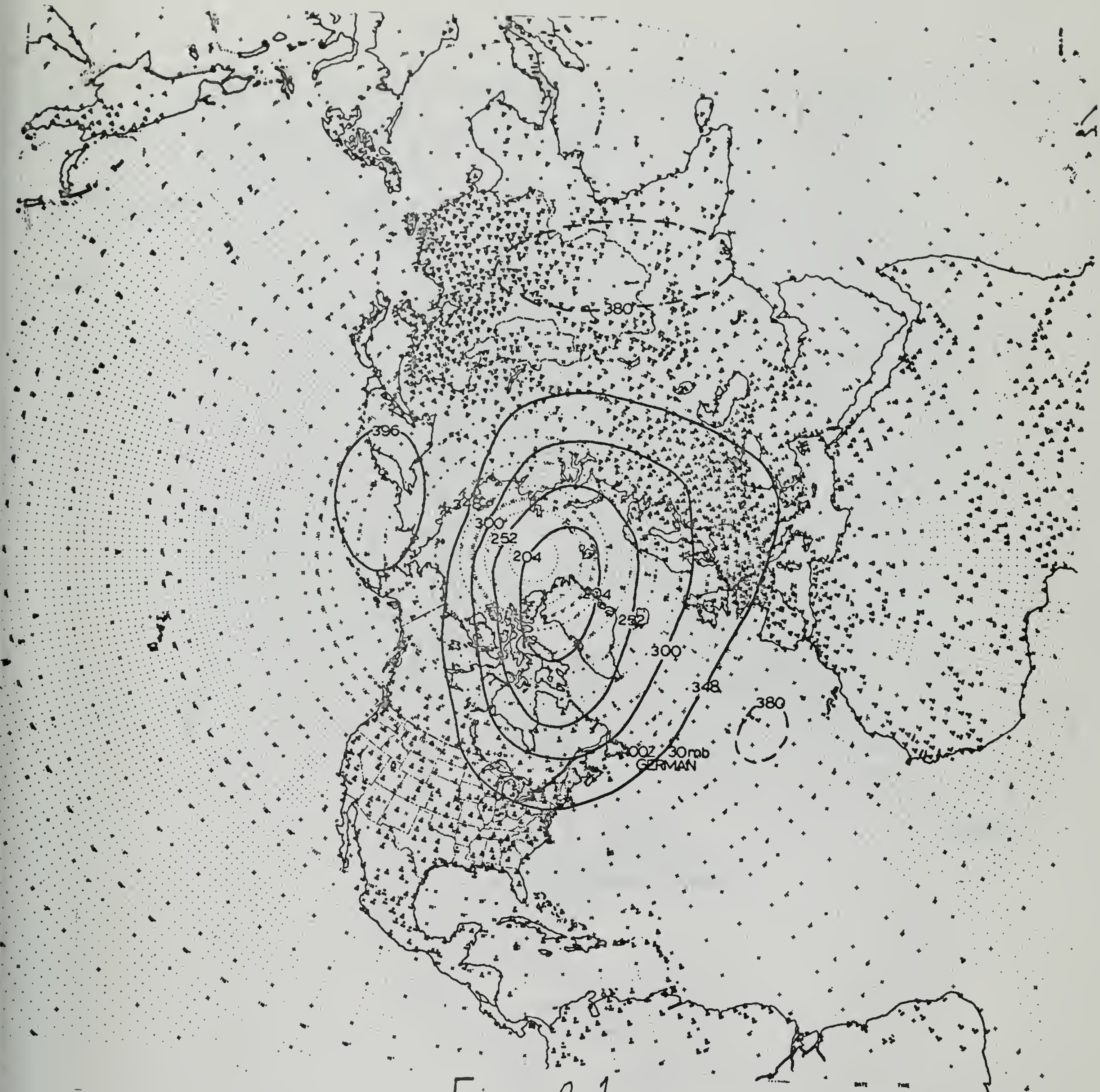


Fig. 21 ht 204 = 22040 m

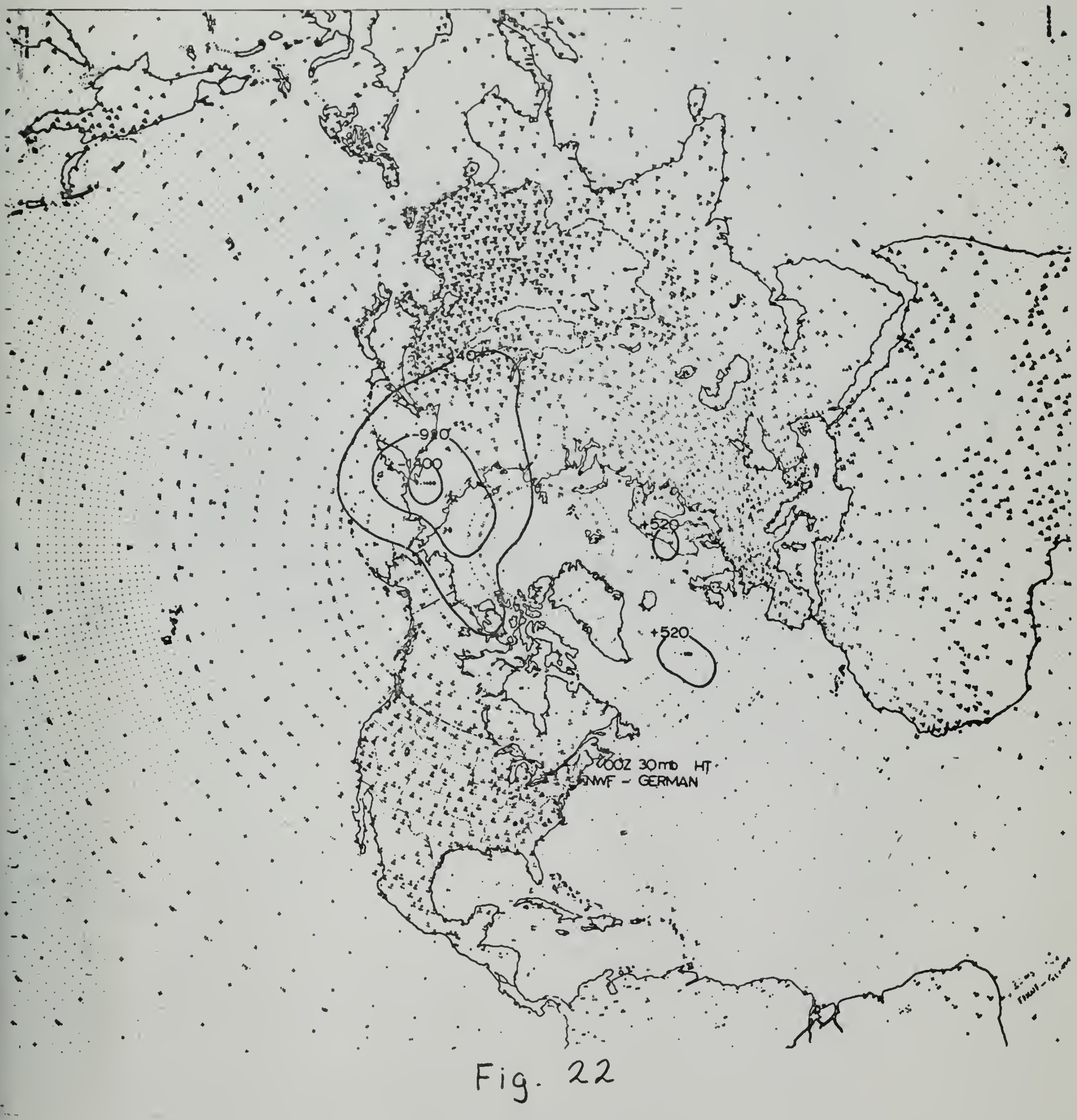


Fig. 22

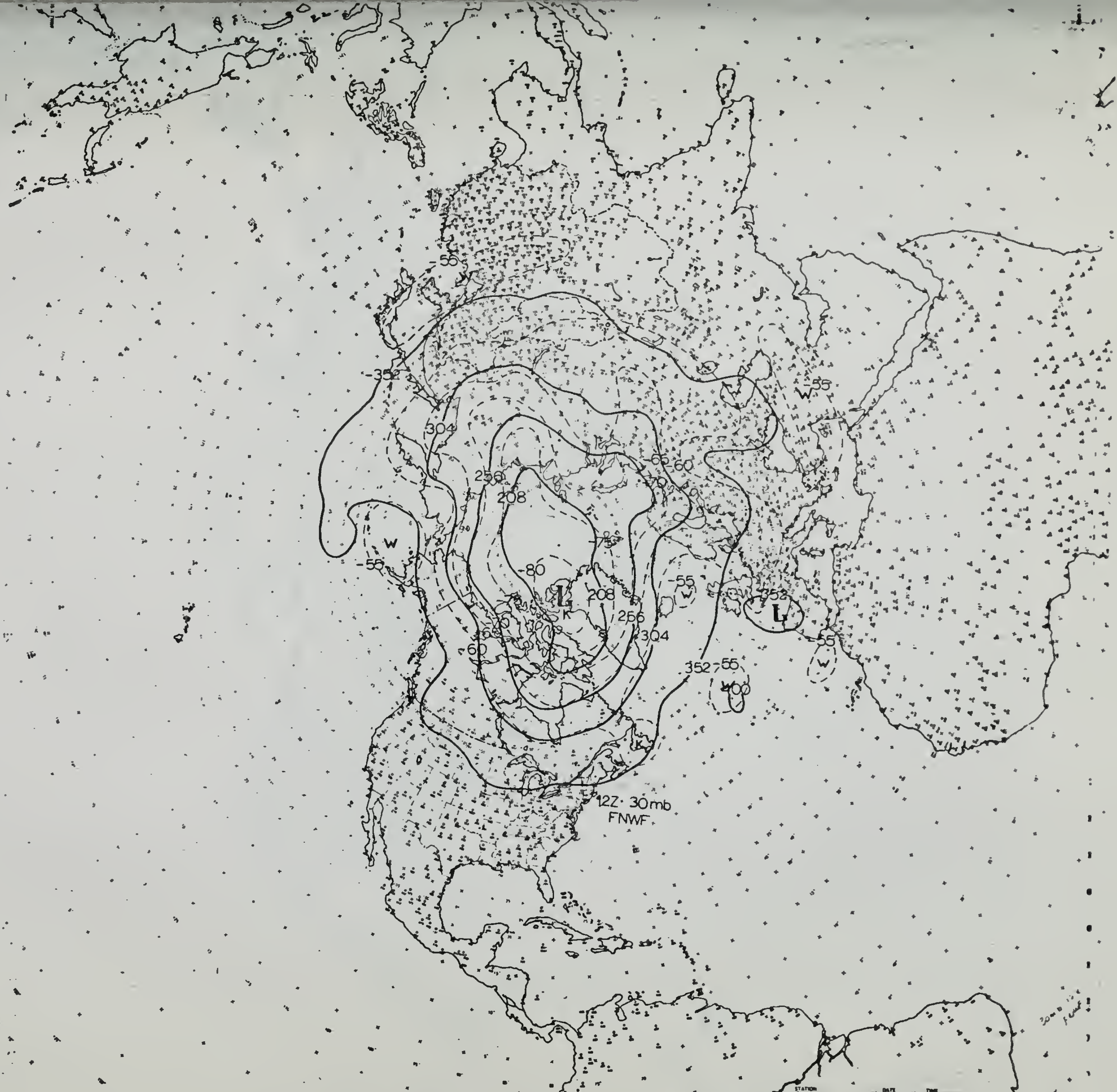


Fig 23

ht 208 = 22080 m
temp -80 = -80C

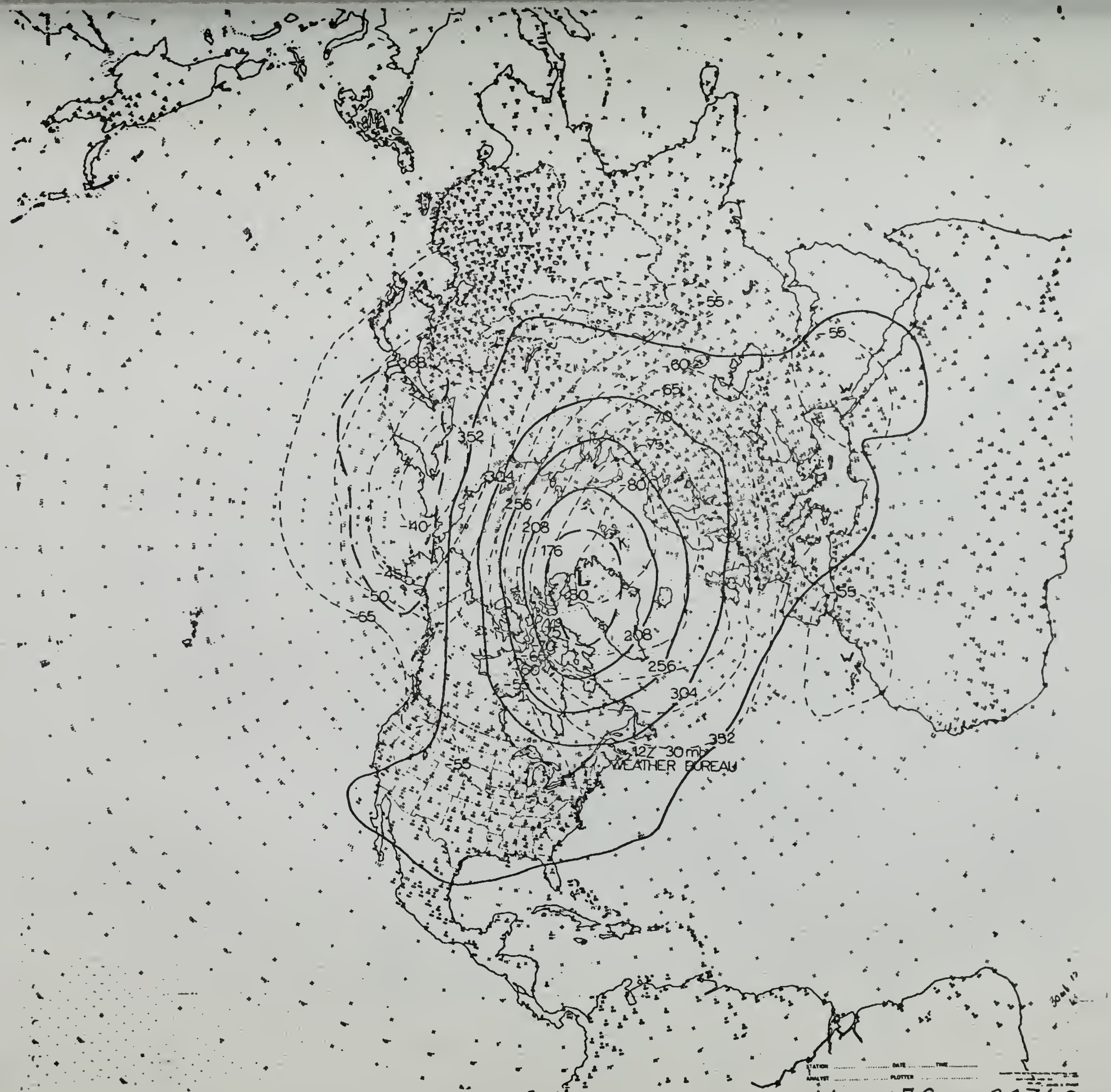


Fig 24

ht 176 = 21760m
temp -80 = -80C

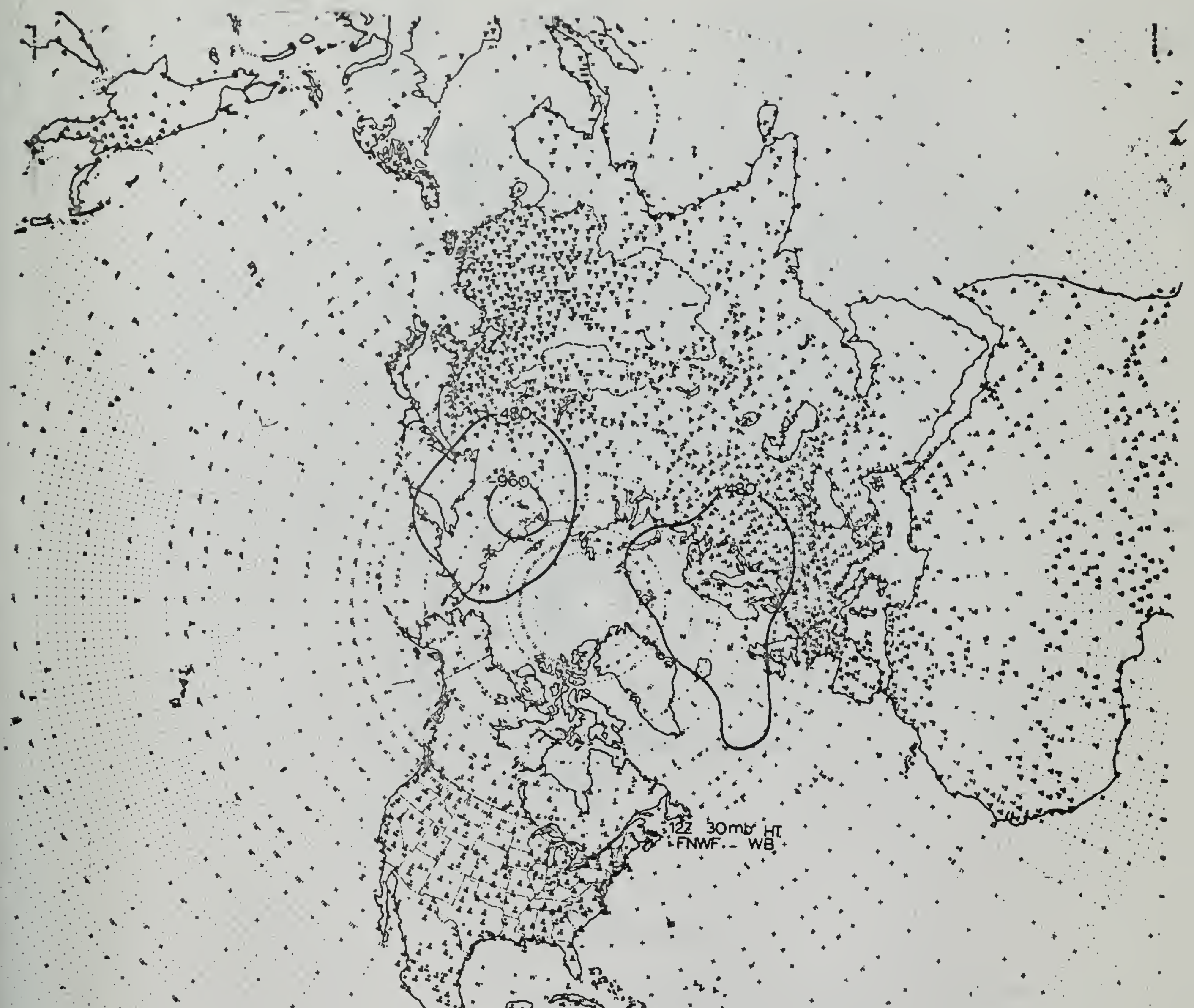


Fig 25

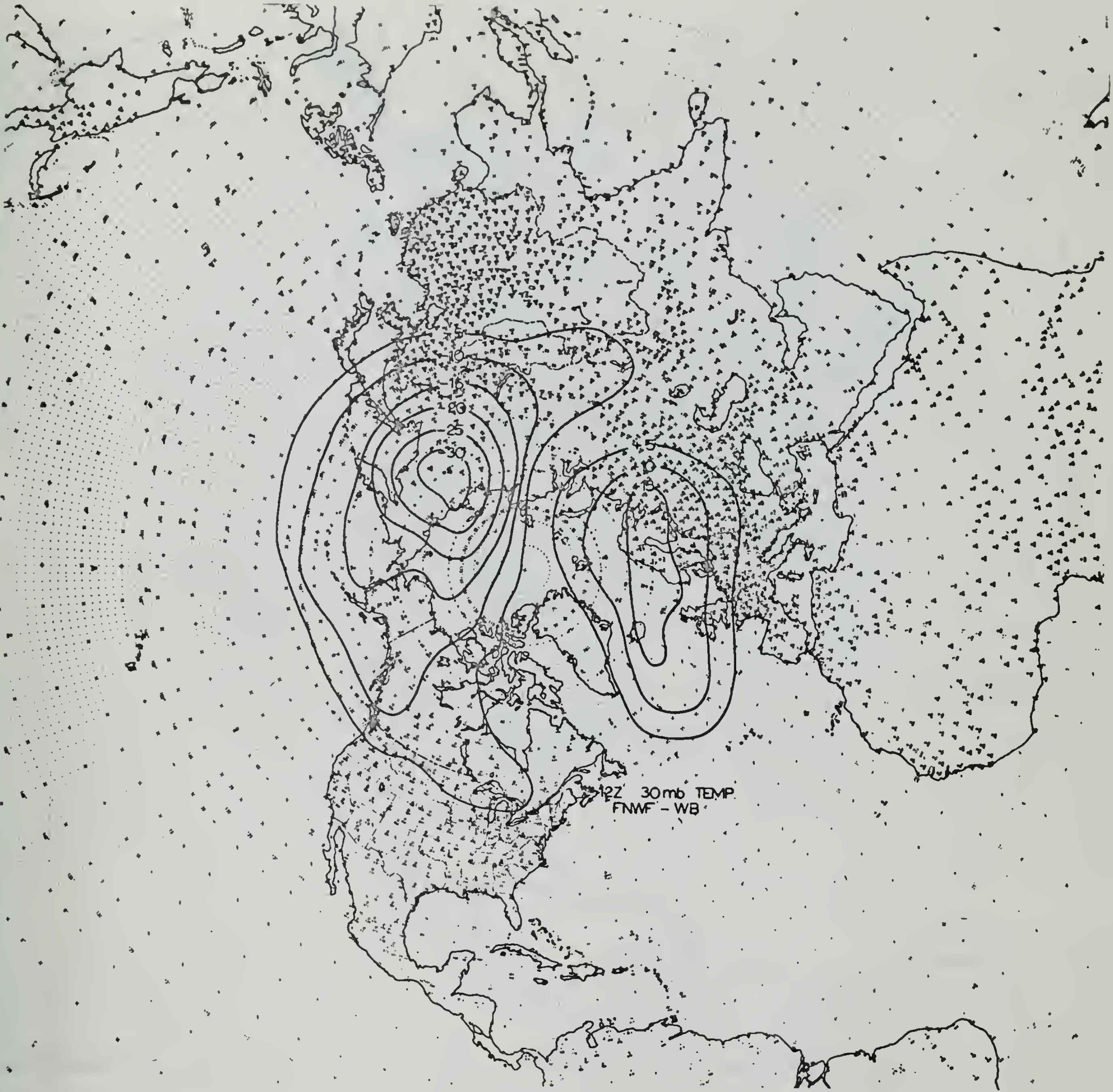


Fig. 26

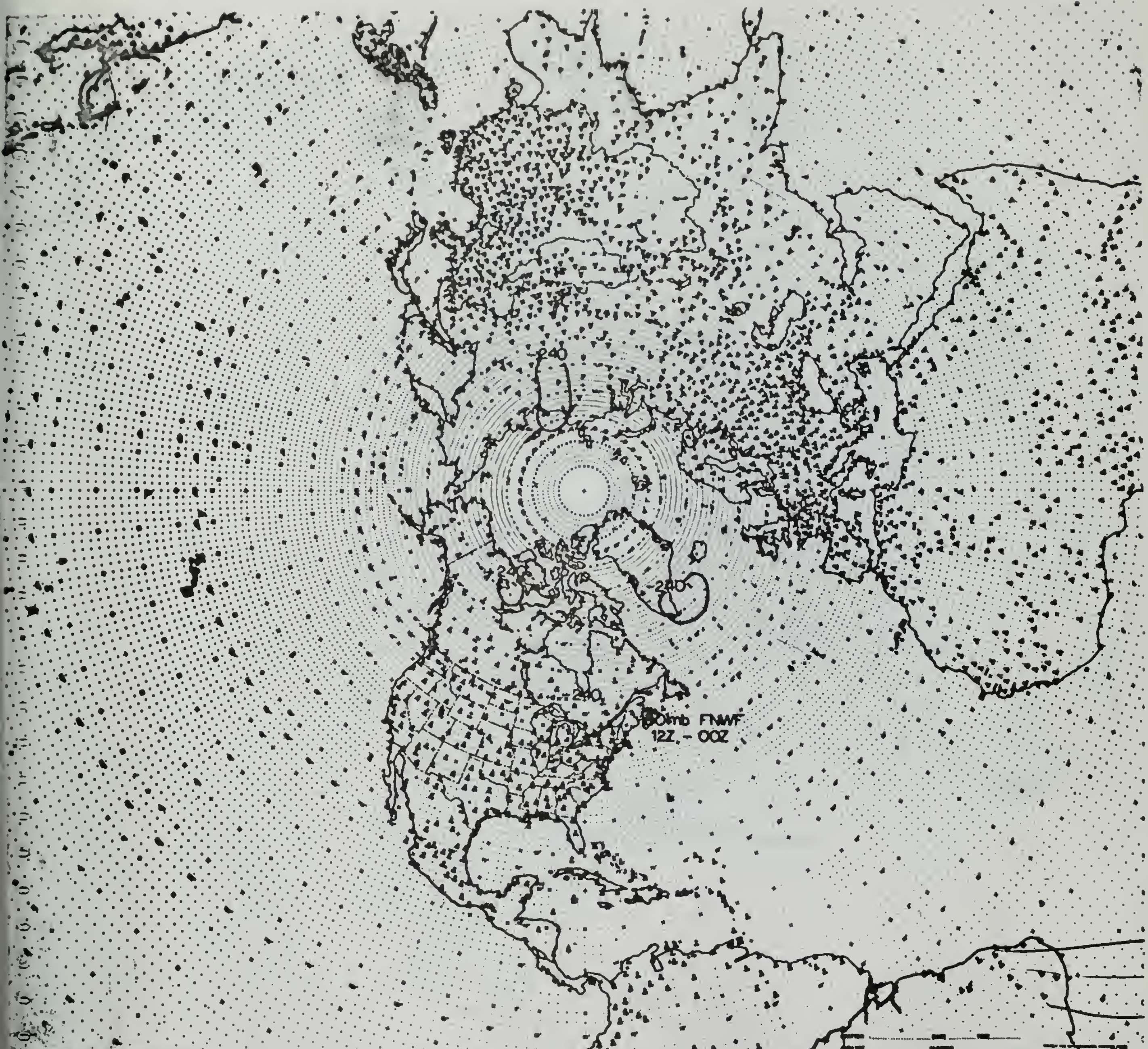


Fig. 27

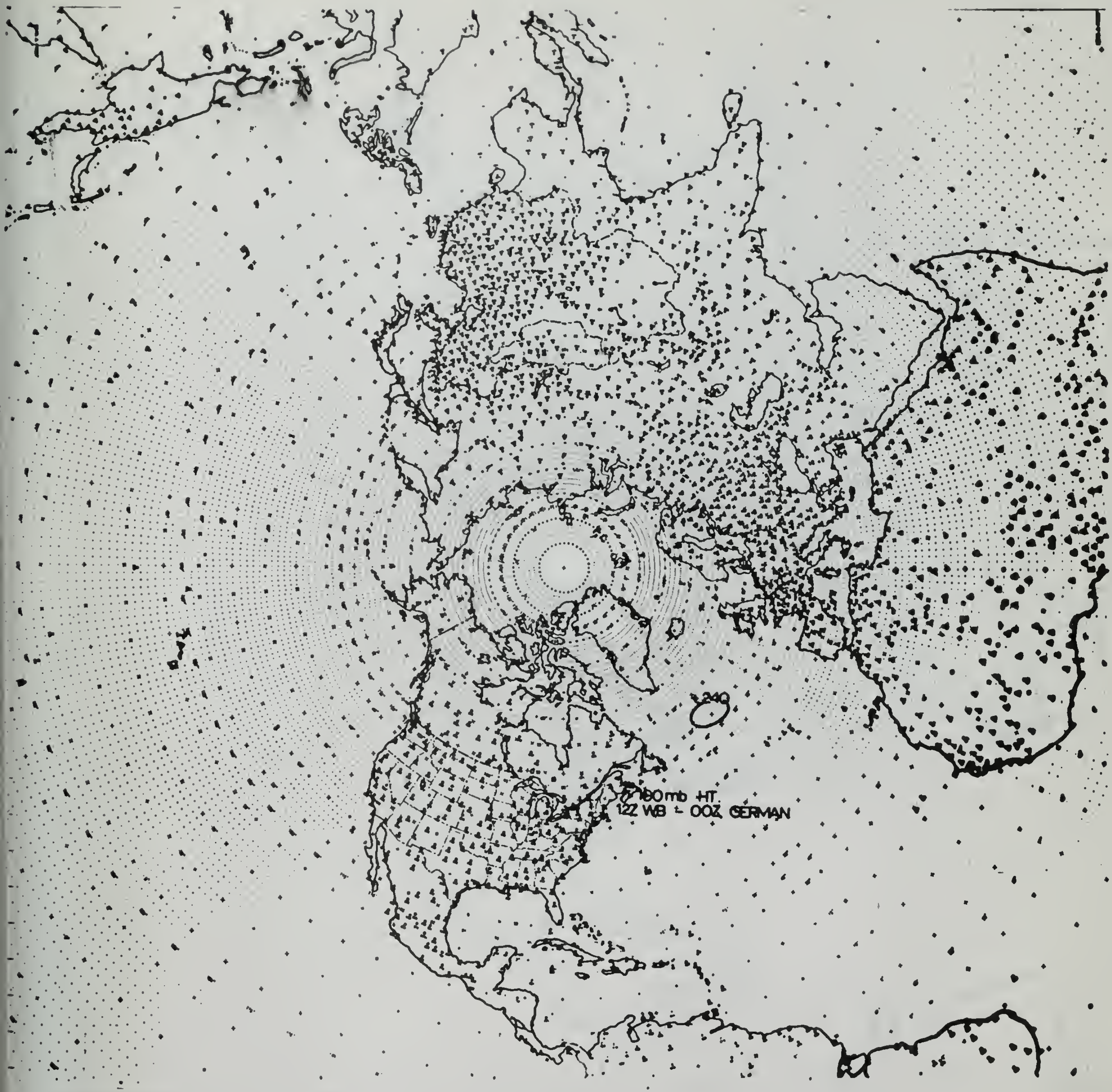


Fig 28

Fig 29

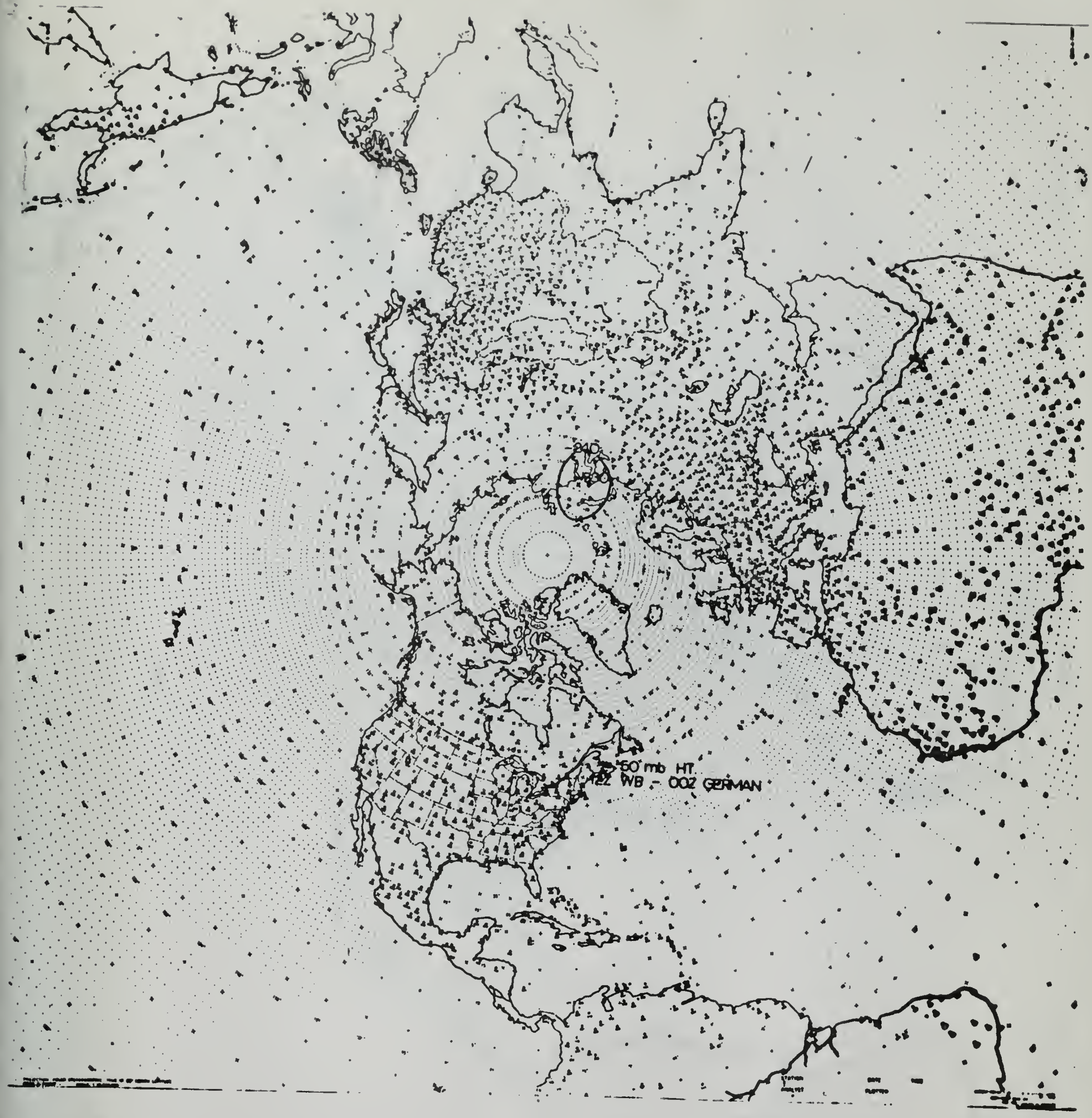


Fig 30

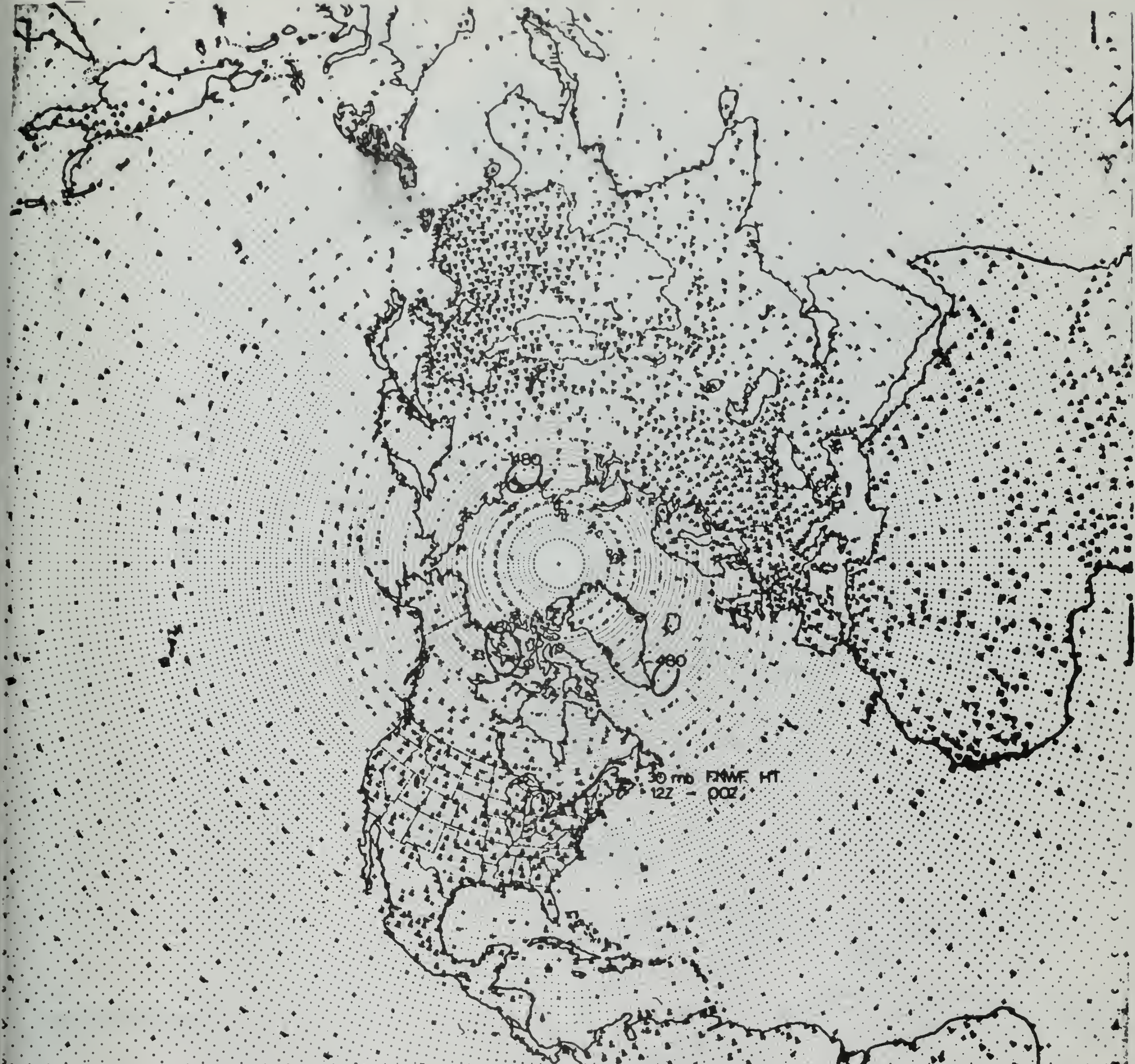


Fig 31

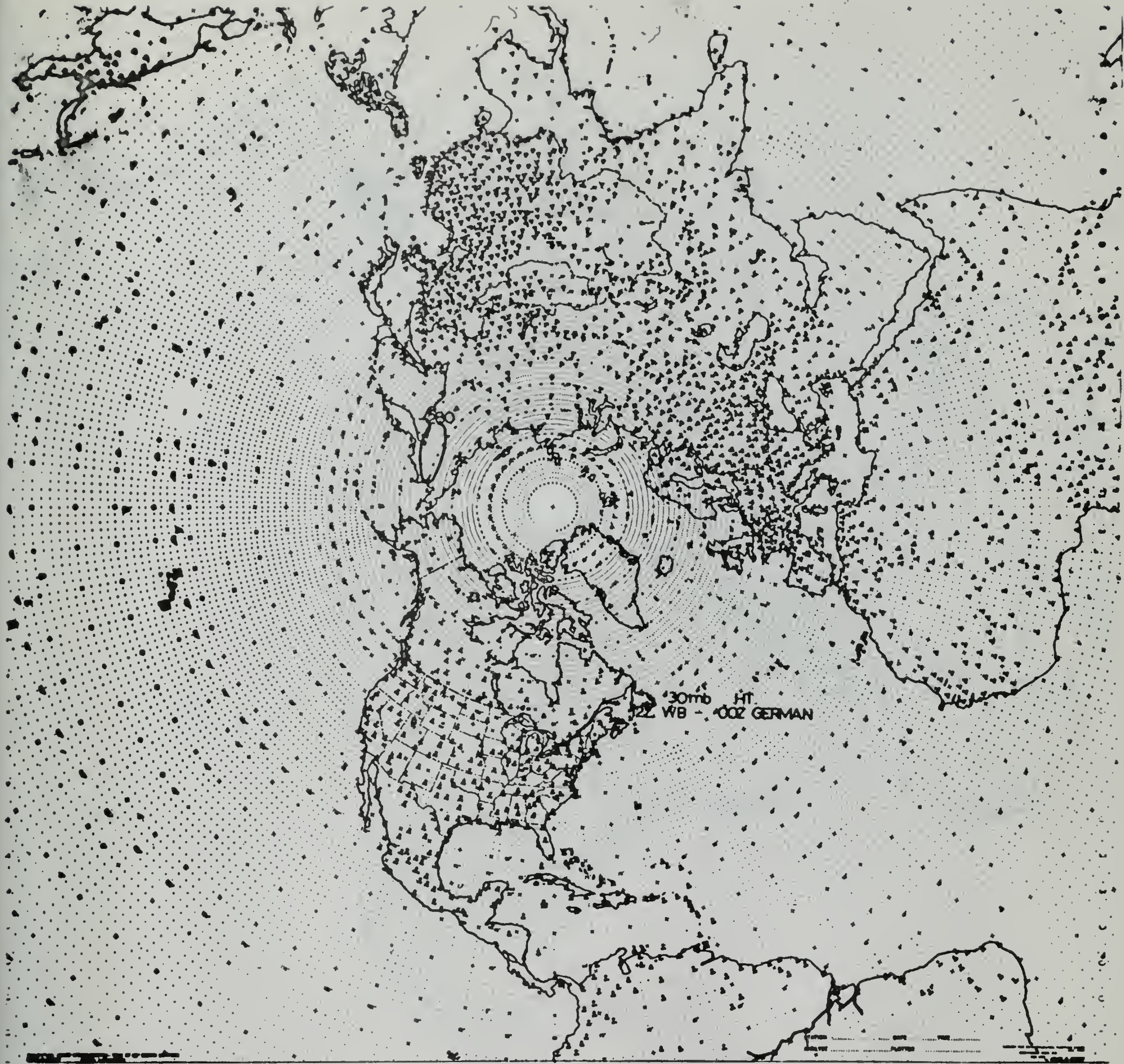


Fig. 32

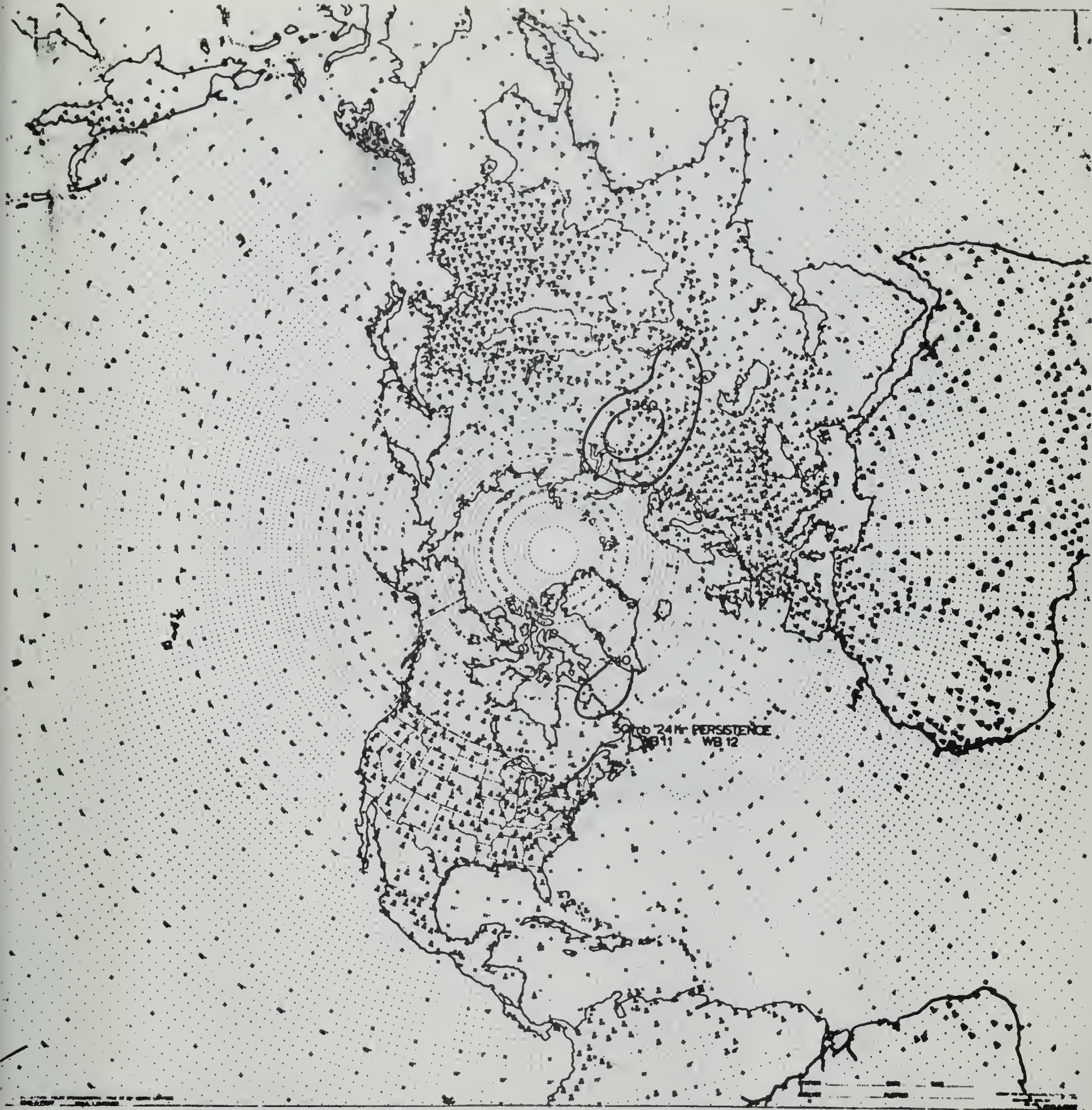


Fig 33

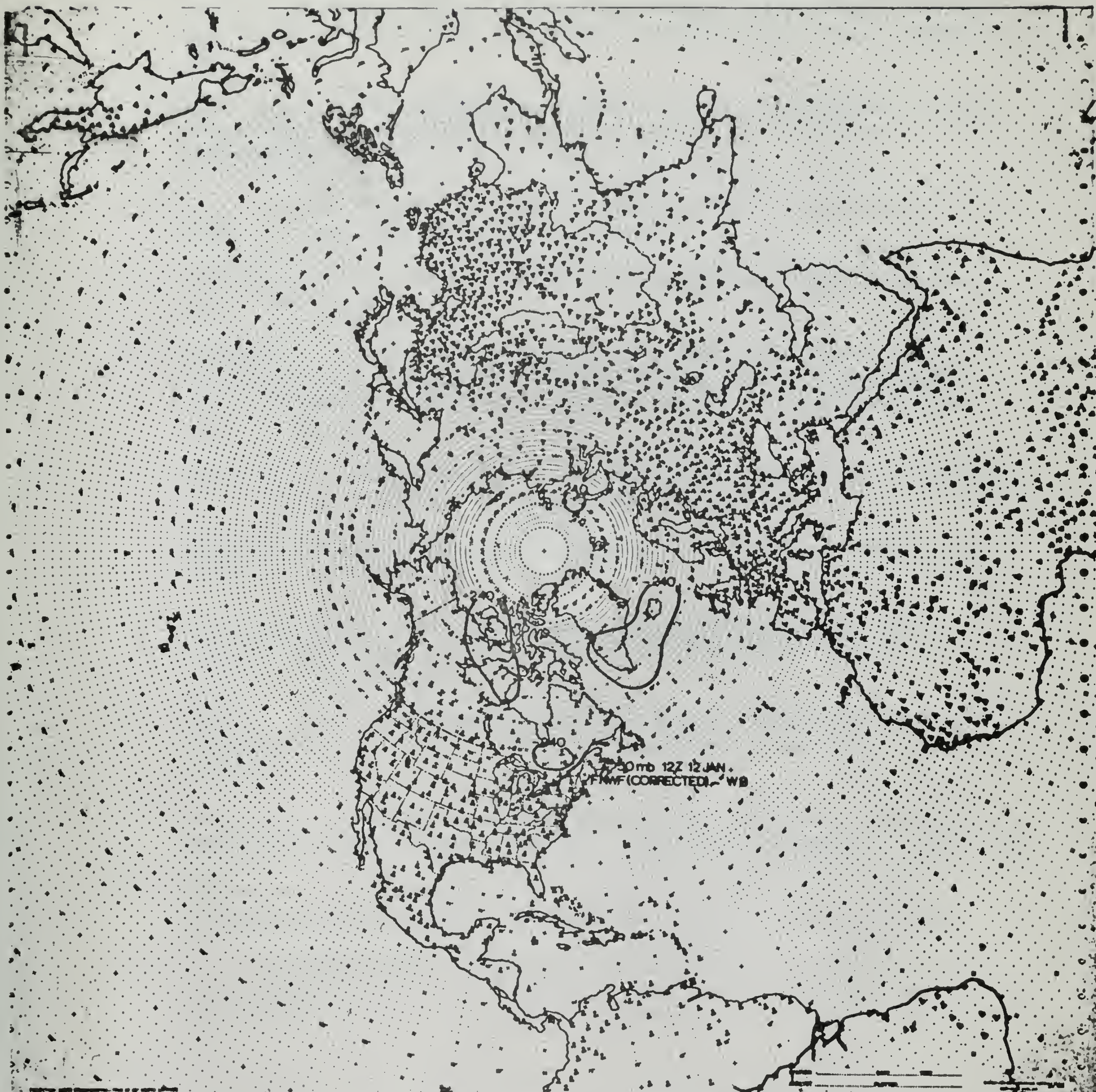


Fig 34

BIBLIOGRAPHY

1. Lea, D. Regression Equations for Vertical Extrapolation of Constant-Pressure-Surface Heights and Temperatures between 200 mb and 30 mb. Presented at the National AMS Meeting, Chicago, March 1961.

2. Cave, Lcdr. D. B. and Ritchie, 1/Lt. F. D. A Verification of the Fleet Numerical Weather Facility's Stratospheric Analyses. USNAVPGSCOL, 1964.

3. U. S. Weather Bureau, Northern Hemispheric Data Tabulations, March, 1963, et. seq., Asheville, N. C., 1963.

4. McCracken, D. D. A Guide to Fortran Programming, John Wiley and Sons. New York, 1963.

5. Kochanski, A. The Construction of 300-, 200-, and 100-mb Maps of the Northern Hemisphere. Appendix to Rpt No. 4 Investigation of the General Circulation of the Atmosphere. J. Bjerknes, UCLA, 1950, pp 13-19.

6. Leviton, R. Height Errors in a Rawin System. AF Surveys in Geophys. No. 60 AFCRC. Bedford, Massachusetts, Dec. 1954.

7. Hoel, P. G. Introduction to Mathematical Statistics. John Wiley and Sons. New York, 1954.

8. U. S. Air Force. Atlas of Monthly Mean Stratosphere Charts, 1955-59, Part 1 and 2. AF Surveys in Geophysics No. 141 AFCRC. Bedford, Massachusetts.

9. Geb, M. et al, Tagliche and mittlere Boden- und 300-mb-Karten der Nordhemisphare. Meteorologische Abhandlungen. Band XXXV, Heft 3, et. seq.

10. Lavoie, R. L. and Wiederanders, Capt. C. J. Objective Wind Fore-Casting over the Tropical Pacific. University of Hawaii. Dec., 1960.

11. Finger, F. G. and Woolf, H. M. IQSY Stratospheric Map Series. Presented at the National AMS Meeting, New York, January, 1965.

12. U. S. Weather Bureau. High Level Extrapolation (Regression Coefficients Recomputed to 5 Decimals). Job #4610, Asheville, N. C. June, 1961

APPENDIX I

The following are the NWRF linear regression equations taken from [12].

Equation	1	$H_{100} = A_1 + A_2H_{200} + A_3T_{200}$
"	2	$T_{100} = A_4 + A_5H_{200} + A_6T_{200}$
"	3	$H_{50} = A_7 + A_8H_{200} + A_9T_{200}$
"	4	$T_{50} = A_{10} + A_{11}H_{200} + A_{12}T_{200}$
"	5	$H_{50} = A_{13} + A_{11}H_{100} + A_{15}T_{100}$
"	6	$T_{50} = A_{16} + A_{17}H_{100} + A_{18}T_{100}$
"	7	$H_{30} = A_{19} + A_{20}H_{100} + A_{21}T_{100}$
"	8	$T_{30} = A_{22} + A_{23}H_{100} + A_{24}T_{100}$
"	9	$H_{30} = A_{25} + A_{26}H_{50} + A_{27}T_{50}$
"	10	$T_{30} = A_{28} + A_{29}H_{50} + A_{30}T_{50}$

where:

A_i = regression coefficient

H_i = actual height in meters of the constant pressure surface i

T_i = actual temperature in degrees Celsius of the constant pressure surface i

H_i and T_i are the computed values of height and temperature of the constant pressure surface i